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Contents

Unit 1 Kinematics 2

Focus on STSE: Sports in Motion 3
Are You Ready? 4

Chapter 1: Motion in a Straight Line 6
1.1 Distance, Position, and Displacement. 8
1.2 Speed and Velocity 14
1.3 Acceleration. 21
1.4 Comparing Graphs of Linear Motion 31
1.5 Five Key Equations for Motion with Uniform Acceleration 36
1.6 Acceleration Near Earth's Surface 40
1.7 **Explore an Issue in Vehicle Safety:** Electronic Speed Limiters for Teen Drivers 44
Investigation 1.2.1: Watch Your Speed 46
Investigation 1.4.1: Uniform Velocity 47
Investigation 1.4.2: Motion Down a Ramp 48
Chapter 1 Summary. 50
Chapter 1 Self-Quiz 51
Chapter 1 Review 52

Chapter 2: Motion in Two Dimensions. 58
2.1 Motion in Two Dimensions—A Scale Diagram Approach 60
2.2 Motion in Two Dimensions—An Algebraic Approach 66
2.3 Projectile Motion 76
2.4 Physics Journal: Galileo Galilei: Sixteenth-Century "New Scientist" 82
2.5 **Explore Applications in Kinematics:** Accelerometers: Accelerating Your Life 84
Investigation 2.3.1: Modelling Projectile Motion 86
Chapter 2 Summary. 88
Chapter 2 Self-Quiz 89
Chapter 2 Review 90

Unit 1 Task: Legendary Legume Launcher 96
Unit 1 Self-Quiz 98
Unit 1 Review. 100

Unit 2 Forces 108

Focus on STSE: Forces and Technology 109
Are You Ready? 110

Chapter 3: Newton's Laws of Motion 112
3.1 Types of Forces 114
3.2 Newton's First Law of Motion. 123
3.3 Newton's Second Law of Motion 130
3.4 Newton's Third Law of Motion. 137
3.5 Using Newton's Laws 142
3.6 Physics Journal: Galileo, Newton, and Hawking. 148
Investigation 3.3.1: Investigating Newton's Second Law 150
Chapter 3 Summary. 152
Chapter 3 Self-Quiz 153
Chapter 3 Review 154

Chapter 4: Applications of Forces 160
4.1 Gravitational Force Near Earth 162
4.2 Friction. 168
4.3 Solving Friction Problems. 173
4.4 Forces Applied to Automotive Technology 179
4.5 Forces Applied to Sports and Research. 184
4.6 **Explore an Issue in Forces:** Mandatory Snow Tires in the Winter? 189
Investigation 4.1.1: Acceleration Due to Gravity and Terminal Speed 191
Investigation 4.2.1: Factors That Affect Friction 192
Investigation 4.2.2: Coefficients of Friction 193
Investigation 4.3.1: Predicting Motion with Friction 194
Chapter 4 Summary. 196
Chapter 4 Self-Quiz 197
Chapter 4 Review 198

Unit 2 Task: Egg Crash Test 204
Unit 2 Self-Quiz 206
Unit 2 Review. 208

Unit 3 Energy and Society 216

Focus on STSE: Greening Energy Use and Production 217

Are You Ready? 218

Chapter 5: Work, Energy, Power, and Society 220

5.1 Work 222

5.2 Energy 230

5.3 Types of Energy and the Law of Conservation of Energy 236

5.4 Efficiency, Energy Sources, and Energy Conservation 242

5.5 Power 250

5.6 **Explore Applications of Renewable Energy Sources:** Going Off the Grid 255

Investigation 5.2.1: Conservation of Energy 257

Investigation 5.5.1: Student Power 258

Chapter 5 Summary 260

Chapter 5 Self-Quiz 261

Chapter 5 Review 262

Chapter 6: Thermal Energy and Society 268

6.1 Warmth and Coldness 270

6.2 Heat 275

6.3 Heat Capacity 281

6.4 States of Matter and Changes of State 288

6.5 Heating and Cooling Systems 296

6.6 **Explore an Issue in Thermal Energy:** Geothermal Systems: Friend or Foe? 300

6.7 Physics Journal: When a Brewer Becomes a Scientist 302

Investigation 6.3.1: Specific Heat Capacity of Brass 304

Investigation 6.4.1: Heating Graph of Water 305

Investigation 6.4.2: Specific Latent Heat of Fusion for Ice 306

Chapter 6 Summary 308

Chapter 6 Self-Quiz 309

Chapter 6 Review 310

Chapter 7: Nuclear Energy and Society 316

7.1 Atoms and Isotopes 318

7.2 Radioactive Decay 323

7.3 Half-Life 330

7.4 Nuclear Fission and Nuclear Power Generation 334

7.5 Nuclear Fusion 342

7.6 **Explore an Application of Nuclear Technology:** Pest Control 348

Investigation 7.5.1: Nuclear Energy: Benefit or Hazard? 350

Chapter 7 Summary 352

Chapter 7 Self-Quiz 353

Chapter 7 Review 354

Unit 3 Task: My School's Sustainable Energy Plan 360

Unit 3 Self-Quiz 362

Unit 3 Review 364

Unit 4 Waves and Sound 372

Focus on STSE: Tsunami of 2004 373

Are You Ready? 374

Chapter 8: Vibrations and Waves 376

8.1 What Is a Vibration? 378

8.2 Types of Mechanical Waves 381

8.3 Wave Characteristics 385

8.4 Determining Wave Speed 388

8.5 Properties of Sound Waves 392

8.6 Physics Journal: The Sound Barrier 398

8.7 **Explore an Issue in Sound:** Noise Pollution 400

Investigation 8.3.1: Investigating Vibrations 402

Investigation 8.4.1: Investigating Two-Dimensional Wave Motion 403

Investigation 8.5.1: Measuring the Speed of Sound 404

Chapter 8 Summary 406

Chapter 8 Self-Quiz 407

Chapter 8 Review 408

Chapter 9: Wave Interactions 414

9.1 Interference of Waves. 416
9.2 Waves at Media Boundaries 420
9.3 Beats 427
9.4 Damping and Resonance. 430
9.5 The Doppler Effect 433
9.6 Physics Journal: Rogue Waves 436
Investigation 9.2.1: Investigating Wave Speed on a String 438
Investigation 9.4.1: Investigating Standing Waves in an Air Column 439
Chapter 9 Summary. 440
Chapter 9 Self-Quiz 441
Chapter 9 Review 442

Chapter 10: Applications of Waves 448

10.1 Human Hearing 450
10.2 Musical Instruments 454
10.3 Acoustics 461
10.4 Structural Safety 464
10.5 Seismic Waves. 466
10.6 Vibrations in Aircraft. 469
10.7 Nature and Sound Waves 472
Investigation 10.1.1: Investigating Frequency, Loudness, and Human Hearing 475
Investigation 10.2.1: Waveforms of Instruments. 476
Investigation 10.3.1: Investigating Acoustic Surfaces 477
Chapter 10 Summary 478
Chapter 10 Self-Quiz. 479
Chapter 10 Review. 480

Unit 4 Task: Applying Waves and Sound to Design. 486
Unit 4 Self-Quiz 488
Unit 4 Review. 490

Unit 5 Electricity and Magnetism 498

Focus on STSE: What Is the Lifespan of a Cellphone? 499
Are You Ready? 500

Chapter 11: Electricity and Its Production. 502

11.1 Electrical Energy and Power Plants. 504
11.2 **Explore an Issue in Generating Electricity:** Clean Coal Technology 508
11.3 Electric Potential Difference 510
11.4 Physics Journal: Is Benjamin Franklin to Blame? 514
11.5 Electric Current 516
11.6 Kirchhoff's Laws 519
11.7 Electrical Resistance. 523
11.8 Resistors in Circuits 527
11.9 Circuit Analysis 531
Investigation 11.8.1: Analyzing Circuits. 536
Chapter 11 Summary 538
Chapter 11 Self-Quiz. 539
Chapter 11 Review. 540

Chapter 12: Electromagnetism 546

12.1 Magnetic Fields. 548
12.2 Oersted's Discovery 553
12.3 Physics Journal: Wireless Electricity 557
12.4 Solenoids 559
12.5 The Motor Principle. 563
12.6 The Direct Current Motor. 567
12.7 **Explore Applications in Electromagnetism:** Magnetic Resonance Imaging. 572

Investigation 12.1.1: Properties of Magnetic Fields . . 574
Investigation 12.4.1: Magnetic Fields around Electromagnets 575
Investigation 12.6.1: Building and Investigating a Prototype Motor 576
Chapter 12 Summary 578
Chapter 12 Self-Quiz 579
Chapter 12 Review 580

Chapter 13: Electromagnetic Induction . . . 586
13.1 Electromagnetic Induction 588
13.2 Lenz's Law 592
13.3 Alternating Current 595
13.4 Electricity Generation 599
13.5 Transformers 605
13.6 Power Plants and the Electrical Grid. 610
Investigation 13.2.1: Investigating Electromagnetic Induction 613
Chapter 13 Summary 614
Chapter 13 Self-Quiz 615
Chapter 13 Review 616

Unit 5 Task: Building a Model Power Plant. . . .622
Unit 5 Self-Quiz 624
Unit 5 Review. 626

Appendix A **Skills Handbook 635**

Appendix B **Reference. 660**

Appendix C **Answers .666**

Glossary 673
Index 679
Credits 687

UNIT 1

Kinematics

OVERALL EXPECTATIONS

- analyze technologies that apply concepts related to kinematics, and assess the technologies' social and environmental impact
- investigate, in qualitative and quantitative terms, linear motion with uniform and non-uniform velocity, and solve related problems
- demonstrate an understanding of linear motion with uniform and non-uniform velocity

BIG IDEAS

- Motion involves a change in the position of an object over time.
- Motion can be described using mathematical relationships.
- Many technologies that apply concepts related to kinematics have societal and environmental implications.

UNIT TASK **PREVIEW**

The challenge in this Unit Task is to design and construct a bean bag launcher. You will need to calibrate the launcher to fire accurately at various target distances. You will compete with your classmates to construct the most accurate launcher. The Unit Task is described in detail on page 96. As you work through the unit, look for Unit Task Bookmarks to see how information in the section relates to the Unit Task.

SPORTS IN MOTION

The interactions among Science, Technology, Society, and the Environment (STSE) make physics relevant to our lives in a million different ways. Sports are just one example. In Canada, hockey is more than just a game. For many, it's an obsession! Hockey is an exciting, fast-paced sport. You can watch players skate down the ice to score the next goal, a defenceman skillfully deflecting the puck out of the opposition player's control, or a goaltender making a difficult glove save. Speed is a critical part of the game, from racing to get to the puck to firing a shot past the goaltender.

Imagine hockey or any other sport without motion and speed—it would not be nearly as entertaining. The rapid acceleration of the puck during a slapshot, the way that a skilled player can rapidly change his or her speed and direction of motion—these high-speed actions are what make a hockey game so exciting. In other sports, motion and speed are just as important for the athlete as for the enjoyment of the fans. You can clearly see the skill of professional athletes in the precision control of a long soccer pass, or of a basketball as it sails through the air in a perfect jumpshot. There is a direct link between how objects move and the level of excitement we experience while watching or playing our favourite sports.

Questions

1. Consider your favourite sport.
    (a) What kinds of motions are required to play this sport? Describe these motions in your own words.
    (b) Describe the type(s) of motion that must be avoided to be successful in your favourite sport.
2. (a) List any advances in technology that have helped to make professionals in your favourite sport more successful.
    (b) How have these advances in technology helped to improve the athlete's speed or motion? Explain your reasoning.
    (c) Research one advance in technology that has helped to make athletes in your favourite sport more successful. Write a paragraph describing how this technology works.
3. How can a better understanding of motion help a participant in your favourite sport avoid injury?
4. What type of protective equipment is required in your favourite sport? Is there any equipment that might help to make your favourite sport safer? How does this equipment affect an athlete's motion?
5. Research how the use of protective equipment in your favourite sport has changed throughout its history. Discuss your findings with a partner.

UNIT 1 ARE YOU READY?

CONCEPTS

- motion
- Cartesian coordinate system
- Pythagorean theorem
- slope of a straight line

SKILLS

- plotting a line graph on a Cartesian coordinate system
- analyzing graphs
- using and converting SI units
- solving an algebraic equation for an unknown variable
- using trigonometry to solve right triangles
- using a protractor and a centimetre ruler precisely
- effectively using a scientific calculator and a spreadsheet
- researching and collecting information
- planning and conducting investigations
- communicating scientific information clearly and accurately

---

Concepts Review

1. Recall the last time you rode in a car. Describe the different types of motion that the vehicle underwent throughout the trip. C
2. An elevator is initially at rest on the second floor of a building. A person on the tenth floor pushes the down button for the elevator. Describe the motion of the elevator as it moves from the second floor to the tenth floor. C
3. What units are used to describe the following: K/U
   (a) distance
   (b) time
   (c) speed
4. You are at the park watching a younger sibling swing back and forth on the swing set. K/U
   (a) Describe how you could measure the distance travelled and the time taken as your sibling swings back and forth.
   (b) What sources of uncertainty exist in this experiment?
   (c) How could you modify your experiment to reduce the uncertainty?
5. (a) Draw a Cartesian coordinate system. Mark and label the compass directions north, south, east, and west on your diagram. Then, mark and label the directions northwest and southeast on your diagram.
   (b) Draw a line 4 cm long, starting at the origin of your Cartesian coordinate system and pointing northwest. T/I
6. A tin can is placed outside just as it starts to rain. **Table 1** contains measurements of the mass of water in the can taken at time intervals of 1 s. Describe the information provided in Table 1. T/I

Table 1 Mass–Time Rainfall Data

t (s)	m (g)
0	6.0
1	9.7
2	13.4
3	17.1
4	20.8
5	24.5
6	28.2
7	31.9
8	35.6
9	39.3
10	43.0

Skills Review

7. (a) Plot a graph of mass versus time using the data in Table 1. Plot time on the horizontal axis.
   (b) Determine an equation to represent the data. Then answer the following questions:
      (i) Describe the graph. What is the relationship between mass and time?
      (ii) Write an equation to determine the slope of the line on the graph, and provide a value for the slope, including the correct units.
      (iii) What information does the slope provide?
      (iv) Would it be valid to extrapolate this graph for another 10 s?
      (v) Using the equation of the graph, determine the mass of water in the can at 5.38 s. T/I C A

8. Copy and complete **Table 2.** T/I

Table 2

Solve for …	Equation	Answer
a	$F = ma$	
t	$v = \frac{d}{t}$	
T	$PV = nRT$	
b	$y = mx + b$	
t	$d = \left(\frac{v_f + v_i}{2}\right)t$	
a	$d = v_i t + \frac{1}{2}at^2$	
D	$AB = \frac{CD}{E}$	
v_f	$v_f^2 = v_i^2 + 2ad$	
J	$J = \frac{(4.0 \times 10^{10})(3.0 \times 10^4)^8}{2.0 \times 10^{-15}}$	

9. Use the Pythagorean theorem to determine the length of the unknown side in each right triangle shown in **Figure 1.** T/I

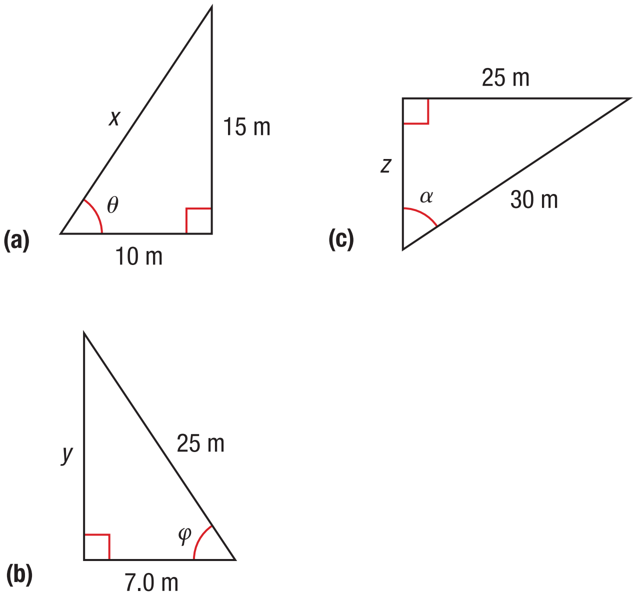

Figure 1

10. Determine the value of each angle in the triangles in Question 9. T/I
    (a) θ
    (b) φ
    (c) α

11. (a) A robin flies a distance of 45 963 cm. How far has it flown in kilometres?
    (b) What is the speed in metres per second of a car that is travelling at 82 km/h?
    (c) What is the speed in kilometres per hour of a 27.78 m/s baseball pitch?
    (d) How many seconds are there in a calendar year, given that a calendar year has 365.24 days in it? T/I

12. Determine each unknown length in **Figure 2.** K/U

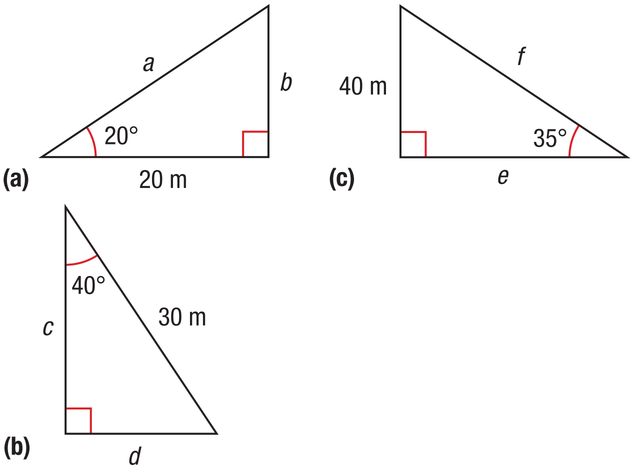

Figure 2

13. The three lines on the distance–time graph in **Figure 3** represent the motion of three objects. T/I
    (a) Which object has travelled farthest at time $t = 5$ s?
    (b) How far has each object travelled at time $t = 3$ s?
    (c) What is the slope of each line?

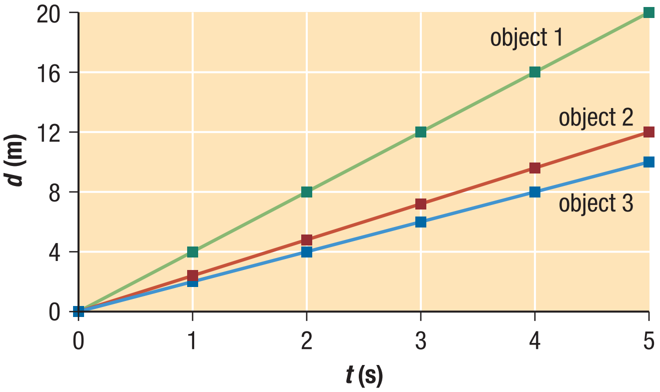

Figure 3

CAREER PATHWAYS PREVIEW

Throughout this unit you will see Career Links in the margins. These links mention careers that are relevant to Kinematics. On the Chapter Summary page at the end of each chapter, you will find a Career Pathways feature that shows you the educational requirements of the careers. There are also some career-related questions for you to research.

CHAPTER 1

Motion in a Straight Line

KEY CONCEPTS

After completing this chapter you will be able to

- explain how distance, position, and displacement are different
- explain how speed, velocity, and acceleration are different
- explain how vectors and scalars are different
- add and subtract vectors using scale diagrams and algebraic methods
- obtain motion information from position–time, velocity–time, and acceleration–time graphs
- solve uniform velocity and uniform acceleration problems using algebraic methods
- describe how the acceleration due to gravity affects the motion of objects close to the surface of Earth
- assess the impact on society and the environment of a technology that applies concepts related to kinematics

What Effects Do Moving Objects Have on Society and the Environment?

Automobiles have been made in North America for over 100 years. As technology has advanced, automobile designs have changed substantially. For example, a 1909 Ford Model T could travel at a maximum speed of approximately 70 km/h. This was considered a frightening speed at the time. Over time, vehicles have become faster. Today, many cars can reach speeds of 200 km/h or more, much higher than the speed limits on any Canadian roads.

Scientists and engineers continue to develop a deeper understanding of motion and the factors that affect it. This knowledge, coupled with technological advances, has enabled them to produce extremely fast experimental land vehicles. The ThrustSSC (SuperSonic Car) reached an astounding speed of 1228 km/h. This extraordinary British-built vehicle was driven by a Royal Air Force pilot and powered by two jet engines. The team that built the ThrustSSC and other competing groups are now attempting to build even faster vehicles.

Although we benefit greatly from motor vehicles that transport huge amounts of goods daily and make travel much easier, we now realize that burning large amounts of fossil fuels has a negative impact on our environment. Fuel consumption for the ThrustSSC was a mind-boggling 55 L of gasoline per kilometre. In comparison, the passenger vehicles you see on the street consume about 0.07 L/km. Many researchers have turned their attention to producing practical vehicles with a lower environmental impact.

Students at the University of Waterloo are moving the technology of passenger vehicles away from fossil fuels altogether. They have designed and constructed a series of solar vehicles called Midnight Sun, which have reached speeds of 117 km/h. The team captured the world record for the longest journey by a solar-powered car.

Faster, more efficient vehicles are an important part of the future of transportation in Canada. Today's students are tomorrow's scientists and engineers. With a sound understanding of the physics of motion, we can improve today's transportation and environmental technologies to help protect our planet.

STARTING **POINTS**

Answer the following questions using your current knowledge. You will have a chance to revisit these questions later, applying concepts and skills from the chapter.

1. Give three examples of scientific language that can be used to describe the motion of objects.
2. Explain how graphs can provide information about the motion of an object.
3. How have the motion capabilities of automobiles changed over the past century?
4. How have changes in technologies that apply concepts about motion affected society and the environment?

Mini Investigation

The Effect of Gravity on the Motion of Objects

Skills: Predicting, Performing, Observing, Analyzing

SKILLS HANDBOOK A2.1

In this activity, you will investigate how mass and shape change the effect of gravity on the motion of objects falling through the air.

Equipment and Materials: 2 spherical objects of different mass; 1 sheet of paper

1. Pick up the two spheres and identify which is heavier.
2. Predict which sphere will reach the floor first if you release both of them simultaneously from the same height. Record your prediction and explain your reasoning.
3. Hold the two spheres at arm's length from your body at the same height. Release the two spheres. Record your observations.

Use caution when dropping the spheres. Do not drop them near your feet or near other students. Pick up the spheres from the floor immediately.

4. Repeat Step 3 with one sphere and a flat sheet of paper. Record your observations.
5. Crumple the piece of paper used in Step 4 into a ball of approximately the same size as one of the spheres.
6. Repeat Step 3 with the crumpled paper ball and the sphere. Record your observations.

A. Did your observations in Step 3 support the prediction you made in Step 2? If not, provide reasons why the prediction was not supported. T/I

B. Did the mass of each sphere in Step 3 affect the time it took the spheres to reach the floor? T/I

C. Compare and contrast your observations for Step 3 with those for Step 4. T/I

D. Compare and contrast your observations for Step 3 with those for Step 6. T/I

1.1

Distance, Position, and Displacement

You see and interact with moving objects every day. Whether you are racing down a ski hill or running for a school bus, motion is part of your everyday life. Long jump athletes are very aware of distance, position, and displacement. Long jumpers run down a stretch of track to a foul line and then jump as far as possible into a sand pit (**Figure 1**). Their goal is to increase the distance of their jumps. To do this, they focus on their speed, strength, and technique. Successful long jumpers master this goal by applying the physics of motion.

Figure 1 Long jumpers attempt to maximize the horizontal distance of their jumps.

LEARNING **TIP**

SI Metric Units
The SI system (le Système international d'unités) provides base units for measuring fundamental physical quantities. Examples of base units are metres (m) for distance and displacement and seconds (s) for time. Some physical quantities use derived units that are defined in terms of a combination of base units. An example of a derived unit is metres per second (m/s), which is the SI unit for speed and velocity.

Describing the Motion of Objects

To understand the motion of objects, we must first be able to describe motion. Physicists use a number of specific terms and units to describe motion. You are likely familiar with many of these terms and units.

Kinematics is the term used by physicists and engineers to describe the study of how objects move. What exactly is motion? **Motion** is a change in the location of an object, as measured by an observer. **Distance**, in physics terms, means the total length of the path travelled by an object in motion. The SI metric base unit for distance is the metre (m). To help you understand the terms that describe motion, imagine that you are at your home in **Figure 2**. You are at the location marked "0 m." If you walk directly from home to your school in a straight line, you will travel a distance of 500 m. If you walk from your school to the library and then return home, you will travel an additional distance of 700 m + 1200 m = 1900 m.

kinematics the study of motion

motion a change in an object's location as measured by a particular observer

distance (*d*) the total length of the path travelled by an object in motion

direction the line an object moves along from a particular starting point

If your friend wants to know how to get to the library from your home, telling him to walk for 1200 m is not very helpful. You also need to tell your friend which direction to go. **Direction** is the line an object moves along from a particular starting point, expressed in degrees on a compass or in terms of the compass points (north, west, east, and south). Directions can also be expressed as up, down, left, right, forward, and backwards. Directions are often expressed in brackets after the distance (or other value). For example, 500 m [E] indicates that the object is 500 m to the east.

CAREER **LINK**

Many branches of engineering use principles of kinematics. To learn more about becoming an engineer,

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Direction is important when describing motion. If the school in Figure 2 is your starting point, the library is in a different direction from your school than your home is. If the library is your starting point, then your school and home are in the same direction.

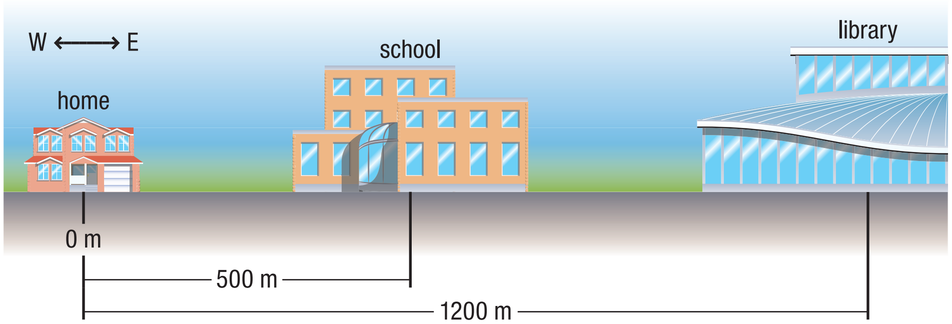

Figure 2 Distance and direction along a straight line

Scalar and Vector Quantities

A **scalar** quantity is a quantity that has magnitude (size) only. Distance is an example of a scalar quantity. Since direction is so important in describing motion, physicists frequently use terms that include direction in their definitions. A **vector** is a quantity that has magnitude (size) and also direction. An arrow is placed above the symbol for a variable when it represents a vector quantity.

scalar a quantity that has only magnitude (size)

vector a quantity that has magnitude (size) and direction

WEB LINK

To review scalar and vector quantities,

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Position and Displacement

Position is the distance and direction of an object from a particular reference point. Position is a vector quantity represented by the symbol $\vec{d}$. Notice the vector arrow above the symbol d. This arrow indicates that position is a vector: it has a direction as well as a magnitude. For example, if home is your reference point, the position of the school in Figure 2 is 500 m [E]. Note that the magnitude of the position is the same as the straight-line distance (500 m) from home to school, but the position also includes the direction (due east [E]). The position of the school from point 0 m can be described by the equation

position ($\vec{d}$) the distance and direction of an object from a reference point

$$\vec{d}_{\text{school}} = 500\text{ m [E]}$$

Now assume that the library is your reference point, or the point 0 m. The position of the school from the reference point (library) can be described by the equation

$$\vec{d}_{\text{school}} = 700\text{ m [W]}$$

Once the position of an object has been described, you can describe what happens to the object when it moves from that position. This is **displacement**—the change in an object's position. Displacement is represented by the symbol $\Delta\vec{d}$. Notice the vector arrow indicating that displacement is a vector quantity. The triangle symbol Δ is the Greek letter delta. Delta is always read as "change in," so $\Delta\vec{d}$ is read as "change in position." As with any change, displacement can be calculated by subtracting the initial position vector from the final position vector:

displacement ($\Delta\vec{d}$) the change in position of an object

$$\Delta\vec{d} = \vec{d}_{\text{final}} - \vec{d}_{\text{initial}}$$

When an object changes its position more than once (experiences two or more displacements), the total displacement $\Delta\vec{d}_{\text{T}}$ of the object can be calculated by adding the displacements using the following equation:

$$\Delta\vec{d}_{\text{T}} = \Delta\vec{d}_1 + \Delta\vec{d}_2$$

Tutorial 1 Calculating Displacement for Motion in a Straight Line

When you walk from one place to another, your position changes. This change in your position is displacement. The displacement can be calculated using your position at the beginning and the end of your journey with the equation $\Delta\vec{d} = \vec{d}_{\text{final}} - \vec{d}_{\text{initial}}$. Remember that position is a vector quantity, so you have to take direction into account. In the following Sample Problems, we will calculate displacements using a range of techniques. Refer to **Figure 3** for the first three Sample Problems.

In Sample Problem 1, we will calculate the displacement of an object with an initial position of 0 m.

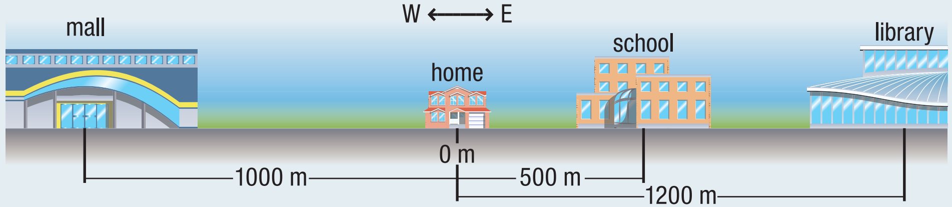

Figure 3

Sample Problem 1: Calculating Displacement from a Zero Starting Point by Vector Subtraction

Imagine that you walk from home to school in a straight-line route. What is your displacement?

Solution

Figure 3 shows that home is the starting point for your journey. When you are at home, your position has not changed. Therefore, your initial position is zero. Your school has a position of 500 m [E] relative to your home.

Given: $\vec{d}_{\text{school}} = 500\ \text{m}\ [\text{E}]$; $\vec{d}_{\text{home}} = 0\ \text{m}$

Required: $\Delta\vec{d}$

Analysis: $\Delta\vec{d} = \vec{d}_{\text{school}} - \vec{d}_{\text{home}}$

Solution:
$$\begin{aligned}\Delta\vec{d} &= \vec{d}_{\text{school}} - \vec{d}_{\text{home}}\\ &= 500\ \text{m}\ [\text{E}] - 0\ \text{m}\\ \Delta\vec{d} &= 500\ \text{m}\ [\text{E}]\end{aligned}$$

Statement: Your displacement when walking from your home to school is 500 m [E].

Sample Problem 2: Calculating Displacement by Vector Subtraction

What is your displacement if you walk from your school to the library? Note that all positions are measured relative to your home.

Given: $\vec{d}_{\text{school}} = 500\ \text{m}\ [\text{E}]$; $\vec{d}_{\text{library}} = 1200\ \text{m}\ [\text{E}]$

Required: $\Delta\vec{d}$

Analysis: $\Delta\vec{d} = \vec{d}_{\text{library}} - \vec{d}_{\text{school}}$

Solution:
$$\begin{aligned}\Delta\vec{d} &= \vec{d}_{\text{library}} - \vec{d}_{\text{school}}\\ &= 1200\ \text{m}\ [\text{E}] - 500\ \text{m}\ [\text{E}]\\ \Delta\vec{d} &= 700\ \text{m}\ [\text{E}]\end{aligned}$$

Statement: Your displacement when walking from school to the library is 700 m [E].

Defining the initial starting position of your motion as 0 m will often make displacement problems simpler. In Sample Problem 2, if we had defined 0 m as being the location of the school, it would have been obvious from the diagram that the displacement from the school to the library is 700 m [E].

Sample Problem 3: Calculating Total Displacement by Vector Addition

One night after working at the library, you decide to go to the mall. What is your total displacement when walking from the library to the mall?

Given: $\Delta\vec{d}_1 = 1200\ \text{m}\ [\text{W}]$; $\Delta\vec{d}_2 = 1000\ \text{m}\ [\text{W}]$ (from Figure 3)

Required: $\Delta\vec{d}_T$

Analysis: In this problem, we are not simply calculating a change in position, we are finding the sum of two different displacements. The displacements are given in Figure 3. To calculate the total displacement, we will need to use vector addition. This is simple if both vectors have the same direction.

If the displacement from the library to your home is represented by $\Delta\vec{d}_1$ and the displacement from your home to the mall is represented by $\Delta\vec{d}_2$, then the total displacement, $\Delta\vec{d}_T$, is given by vector addition of these two displacements:

$$\Delta\vec{d}_T = \Delta\vec{d}_1 + \Delta\vec{d}_2$$

Solution:
$$\begin{aligned}\Delta\vec{d}_T &= \Delta\vec{d}_1 + \Delta\vec{d}_2\\ &= 1200\ \text{m}\ [\text{W}] + 1000\ \text{m}\ [\text{W}]\\ \Delta\vec{d}_T &= 2200\ \text{m}\ [\text{W}]\end{aligned}$$

Statement: When walking from the library to the mall, you experience a displacement of 2200 m [W].

Sample Problem 4: Calculating Total Displacement by Adding Displacements in Opposite Directions

A dog is practising for her agility competition. She leaves her trainer and runs 80 m due west to pick up a ball. She then carries the ball 27 m due east and drops it into a bucket. What is the dog's total displacement?

Solution

In this problem, the given values are displacements. To calculate the total displacement, we will add these two displacement vectors.

Given: $\Delta\vec{d}_1 = 80\text{ m }[\text{W}]$; $\Delta\vec{d}_2 = 27\text{ m }[\text{E}]$

Required: $\Delta\vec{d}_\text{T}$

Analysis: $\Delta\vec{d}_\text{T} = \Delta\vec{d}_1 + \Delta\vec{d}_2$

Solution:

$$\begin{aligned}\Delta\vec{d}_\text{T} &= \Delta\vec{d}_1 + \Delta\vec{d}_2\\ &= 80\text{ m }[\text{W}] + 27\text{ m }[\text{E}]\end{aligned}$$

At this point, it appears that we have a problem. We need to add a vector with a direction [W] to a vector with a direction [E]. We can transform this problem so that both vectors point in the same direction. To do so, consider the direction [E] to be the same as "negative" [W]. The vector 27 m [E] is the same as –27 m [W]. We can therefore rewrite the equation as follows.

$$\begin{aligned}&= 80\text{ m }[\text{W}] - 27\text{ m }[\text{W}]\\ \Delta\vec{d}_\text{T} &= 53\text{ m }[\text{W}]\end{aligned}$$

Statement: The dog's total displacement is 53 m [W].

Practice

1. A golfer hits a ball from a golf tee at a position of 16.4 m [W] relative to the clubhouse. The ball comes to rest at a position of 64.9 m [W] relative to the clubhouse. Determine the displacement of the golf ball. T/I [ans: 48.5 m [W]]
2. A rabbit runs 3.8 m [N] and stops to nibble on some grass. The rabbit then hops 6.3 m [N] to scratch against a small tree. What is the rabbit's total displacement? T/I [ans: 10.1 m [N]]
3. A skateboarder slides 4.2 m up a ramp, stops, and then slides 2.7 m down the ramp before jumping off. What is his total displacement up the ramp? T/I [ans: 1.5 m [up]]

Vector Scale Diagrams

In Tutorial 1, you used algebra to determine the displacement of an object in a straight line. However, there is another method you can use to solve displacement problems: vector scale diagrams. **Vector scale diagrams** show the vectors associated with a displacement drawn to a particular scale. A vector can be represented by a **directed line segment**, which is a straight line between two points with a specific direction. Line segments have magnitude only (**Figure 4(a)**). A directed line segment is a line segment with an arrowhead pointing in a particular direction (**Figure 4(b)**). For example, $\overrightarrow{AB}$ is a line segment in the direction from point A to point B. Line segment $\overrightarrow{BA}$ is the same line segment but in the direction from point B to point A (**Figure 4(c)**). A directed line segment that represents a vector always has two ends. The end with the arrowhead is referred to as the tip. The other end is the tail. A vector scale diagram is a representation of motion using directed line segments drawn to scale with arrowheads to show their specific directions. Vector scale diagrams are very useful in measuring the total displacement of an object from its original position.

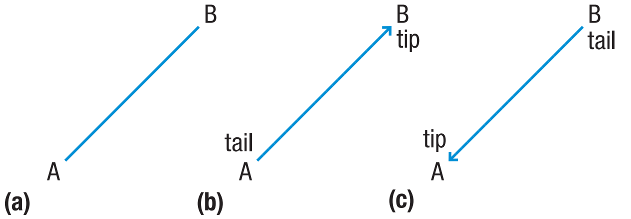

Figure 4 (a) A line segment (b) Directed line segment $\overrightarrow{AB}$ (c) Directed line segment $\overrightarrow{BA}$

vector scale diagram a vector diagram drawn using a specific scale

directed line segment a straight line between two points with a specific direction

CAREER **LINK**

Geomatics technicians collect data using GPS, surveying, and remote sensing. They also record data using geographic information systems (GIS). GIS analysts capture and manage spatial information for use in government and industry. To learn more about becoming a geomatics technician or GIS analyst,

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Consider two displacements, $\Delta\vec{d}_1$ = 700 m [W] and $\Delta\vec{d}_2$ = 500 m [W]. We can determine the total displacement that results from adding these vectors together by drawing a vector scale diagram. In general, when drawing a vector scale diagram, you should choose scales that produce diagrams approximately one-half to one full page in size. The larger the diagram, the more precise your results will be.

Figure 5 shows a vector diagram drawn to a scale where 1 cm in the diagram represents 100 m in the real world. Note that each vector in Figure 5 has a tip (the end with an arrowhead) and a tail (the other end). Vectors can be added by joining them tip to tail. This is similar to using a number line in mathematics. Thus, after applying our chosen scale, Figure 5 shows $\Delta\vec{d}_1$ drawn as a vector 7.0 cm in length pointing due west. The tip of $\Delta\vec{d}_1$ is joined to the tail of $\Delta\vec{d}_2$. In other words, the displacement $\Delta\vec{d}_2$ is drawn as a directed line segment that is 5.0 cm long pointing due west, starting where the displacement $\Delta\vec{d}_1$ ends. The total displacement, $\Delta\vec{d}_T$, is the displacement from the tail, or start, of the first vector to the tip, or end, of the second vector. In this case, $\Delta\vec{d}_T$ points due west and has a length of 12 cm. Converting this measurement by applying our scale gives a total displacement of 1200 m [W].

For straight-line motion, vector scale diagrams are not very complex. We will look at more advanced vector scale diagrams in Chapter 2 when we consider motion in two dimensions.

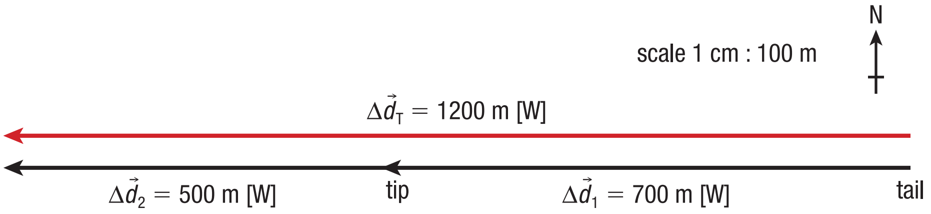
N
scale 1 cm : 100 m
$\Delta\vec{d}_T = 1200$ m [W]
$\Delta\vec{d}_2 = 500$ m [W]
tip
$\Delta\vec{d}_1 = 700$ m [W]
tail

Figure 5 Vector scale diagram

Tutorial 2 Determining Total Displacement for Two Motions in Opposite Directions Using Vector Scale Diagrams

In the following Sample Problem, we will determine displacement by using vector scale diagrams. Consider an example in which motion occurs in two opposite directions.

Sample Problem 1: Using a Vector Scale Diagram to Determine the Total Displacement for Two Motions in Opposite Directions

Imagine that you are going to visit your friend. Before you get there, you decide to stop at the variety store. If you walk 200 m [N] from your home to the store, and then travel 600 m [S] to your friend's house, what is your total displacement?

Solution

Let your initial displacement from your home to the store be $\Delta\vec{d}_1$ and your displacement from the store to your friend's house be $\Delta\vec{d}_2$.

Given: $\Delta\vec{d}_1 = 200$ m [N]; $\Delta\vec{d}_2 = 600$ m [S]

Required: $\Delta\vec{d}_T$

Analysis: $\Delta\vec{d}_T = \Delta\vec{d}_1 + \Delta\vec{d}_2$

Solution: Figure 6 shows the given vectors, with the tip of $\Delta\vec{d}_1$ joined to the tail of $\Delta\vec{d}_2$. The resultant vector $\Delta\vec{d}_T$ is drawn in red, from the tail of $\Delta\vec{d}_1$ to the tip of $\Delta\vec{d}_2$. The direction of $\Delta\vec{d}_T$ is [S]. $\Delta\vec{d}_T$ measures 4 cm in length in Figure 6, so using the scale of 1 cm : 100 m, the actual magnitude of $\Delta\vec{d}_T$ is 400 m.

Statement: Relative to your starting point at your home, your total displacement is 400 m [S].

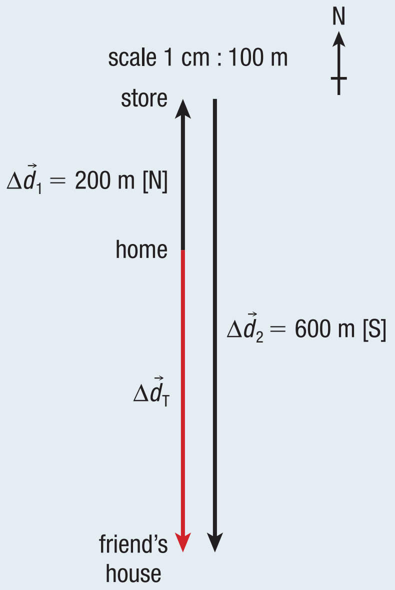

Figure 6 Solution scale diagram for adding vectors with a change in direction

Practice

1. A car drives 73 m [W] to a stop sign. It then continues on for a displacement of 46 m [W]. Use a vector scale diagram to determine the car's total displacement. T/I C [ans: 120 m [W]]
2. A robin flies 32 m [S] to catch a worm and then flies 59 m [N] back to its nest. Use a vector scale diagram to determine the robin's total displacement. T/I C [ans: 27 m [N]]

1.1 Summary

- Motion involves a change in the position of an object.
- Motion can be described using mathematical relationships.
- A scalar is a quantity that has magnitude (size) only.
- A vector is a quantity that has magnitude (size) and direction.
- You can determine the displacement of an object by subtracting the start position from the end position.
- You can determine total displacement by adding two or more displacements together algebraically or by using a vector scale diagram.
- Vectors can be added by joining them tip to tail.

1.1 Questions

1. Which of the following quantities are vectors, and which are scalars? Be sure to explain the reasoning for your answer. K/U C
   (a) A bird flies a distance of 20 m.
   (b) A train is travelling at 100 km/h due north.
   (c) It takes an athlete 10.37 s to run 100 m.
2. Explain the following in your own words: K/U C
   (a) the difference between position and displacement
   (b) the difference between distance and displacement
3. What is the displacement of a locomotive that changes its position from 25 m [W] to 76 m [W]? T/I
4. A car changes its position from 52 km [W] to 139 km [E]. What is the car's displacement? T/I
5. Determine the total displacement for each of the following motions by algebraic methods and by using scale diagrams. T/I C
   (a) $\Delta\vec{d}_1 = 10\text{ m [W]}$; $\Delta\vec{d}_2 = 3.0\text{ m [W]}$
   (b) $\Delta\vec{d}_1 = 10\text{ m [W]}$; $\Delta\vec{d}_2 = 3.0\text{ m [E]}$
   (c) $\Delta\vec{d}_1 = 28\text{ m [N]}$; $\Delta\vec{d}_2 = 7.0\text{ m [S]}$
   (d) $\Delta\vec{d}_1 = 7.0\text{ km [W]}$; $\Delta\vec{d}_2 = 12\text{ km [E]}$; $\Delta\vec{d}_3 = 5.0\text{ km [W]}$
6. A person walks 10 paces forward followed by 3 paces forward, and finally 8 paces backwards. T/I C
   (a) Draw a vector scale diagram representing this person's motion. Use a scale of 1 cm = 1 pace.
   (b) Check your answer by pacing out this motion yourself. How close is your experimental result to that predicted by your vector scale diagram?

1.2 Speed and Velocity

If you have been a passenger in a car or are taking driving lessons, speed is something you have thought about. Knowing the speed at which a vehicle is moving is important for safety. Excessive speed is a contributing factor in many collisions.

Speed can be measured in different ways. Police use laser speed devices to detect the speed of moving vehicles (**Figure 1**). In the laboratory, scientists and engineers can use electronic devices such as motion sensors to measure speed.

Figure 1 A laser speed device can accurately measure the speed of an oncoming vehicle.

Average Speed

The **average speed** of a moving object is the total distance travelled divided by the total time elapsed. You are probably familiar with the speedometer of a passenger vehicle, which tells the speed of the vehicle in kilometres per hour (km/h). However, the SI unit for speed is metres per second (m/s).

average speed (v_{av}) the total distance travelled divided by the total time taken to travel that distance

You do not need a special device like a police speed device to measure speed. If you know the distance travelled and the time it took an object to travel that distance, you can calculate the average speed of the object using the equation

$$v_{av} = \frac{\Delta d}{\Delta t}$$

where v_{av} is the average speed, Δd is the distance travelled, and Δt is the change in time. Like distance, speed is a scalar quantity. In the following Tutorial, we will determine the average speed of an object using this equation.

Investigation **1.2.1**

Watch Your Speed (p. 46)
In this investigation you will use the average speed equation to determine average speed in a study of vehicles passing an observation point.

Tutorial 1 Calculating Average Speed

The following Sample Problems will demonstrate how to use the equation for average speed.

Sample Problem 1: Determining Average Speed

Your dog runs in a straight line for a distance of 43 m in 28 s. What is your dog's average speed?

Given: $\Delta d = 43$ m; $\Delta t = 28$ s

Required: v_{av}

Analysis: $v_{av} = \frac{\Delta d}{\Delta t}$

Solution:
$$\begin{aligned} v_{av} &= \frac{\Delta d}{\Delta t} \\ &= \frac{43\text{ m}}{28\text{ s}} \\ v_{av} &= 1.5\text{ m/s} \end{aligned}$$

Statement: Your dog's average speed is 1.5 m/s.

Sample Problem 2: Determining the Distance Travelled by a Ball Moving at Constant Speed

A baseball rolls along a flat parking lot in a straight line at a constant speed of 3.8 m/s. How far will the baseball roll in 15 s?

Given: $v_{av} = 3.8$ m/s; $\Delta t = 15$ s

Required: Δd

Analysis: $v_{av} = \dfrac{\Delta d}{\Delta t}$

$$\Delta d = v_{av}\Delta t$$

Solution: $\Delta d = v_{av}\Delta t$

$$= \left(3.8\,\frac{\text{m}}{\cancel{\text{s}}}\right)(15\,\cancel{\text{s}})$$

$$\Delta d = 57\text{ m}$$

Statement: The ball will roll 57 m in 15 s.

Practice

1. A paper airplane flies 3.7 m in 1.8 s. What is the airplane's average speed? T/I [ans: 2.1 m/s]
2. A cheetah can run at a maximum speed of 30.0 km/h, or 8.33 m/s. How far can a cheetah run in 3.27 s? T/I [ans: 27.2 m]
3. How long does it take a rock to fall through 2.8 m of water if it falls at a constant speed of 1.2 m/s? T/I [ans: 2.3 s]

LEARNING TIP

Rounding in Calculations

As a general rule, round final answers to the same number of significant digits as the given value with the fewest significant digits. Take extra care when rounding digits with multiple parts. You will see in this book that extra digits are carried in intermediate calculations. For more help with rounding, refer to the Skills Handbook.

Research This

Searching for Speeders

Skills: Researching, Analyzing, Communicating, Identifying Alternatives, Defending a Decision

SKILLS HANDBOOK **A5**

A laser speed device is used by police officers to measure the speed of moving vehicles. This device sends a pulse of infrared laser light at the speed of light (3.0×10^8 m/s) toward a moving vehicle. The laser pulse reflects off the vehicle and returns to a sensor on the speed device. A computer chip in the speed device determines the time it took for the pulse to travel to and from the moving vehicle. The speed device uses one half of this very short time and the speed of light to calculate the distance to the moving vehicle. The speed device's computer uses multiple distance readings to determine how the vehicle's distance is changing with time and then calculates the vehicle's speed. Modern speed devices send thousands of pulses of light each second, providing a high level of accuracy.

1. Conduct research to investigate how common laser speed devices are in the region where you live.
2. Investigate how speed affects the number of automobile collisions and fatalities in Canada.
3. Investigate alternative methods the police could use to determine the speed of a vehicle.

A. Does the use of laser speed devices have an impact on the number of automobile collisions and fatalities in Canada? K/U

B. Do you feel that the use of laser speed devices is the preferred way for police to monitor the speed of automobiles? C

C. Laser speed devices and video recorders can now be used to capture the speed of a moving vehicle, the vehicle's licence plate number, the date, and the time in the same image. If these devices are set in a fixed position, they can operate without the need for a police officer to be present. Data can be collected electronically and speeders can be sent a ticket through the mail. Do you support the use of devices like these in Ontario? Justify your decision. C A

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Average Velocity

average velocity ($\vec{v}_{av}$) the total displacement, or change in position, divided by the total time for that displacement

The **average velocity** of an object in motion is its total displacement, or change in position, divided by the total time taken for the motion. Velocity describes change in position over time. For instance, a cyclist travelling east at a constant speed of 11 m/s has a velocity of 11 m/s [E]. Since it has direction and magnitude, average velocity is a vector quantity. The SI unit for velocity is metres per second (m/s). The symbol for average velocity is $\vec{v}_{av}$.

position–time graph a graph describing the motion of an object, with position on the vertical axis and time on the horizontal axis

A **position–time graph** is a graph that describes the motion of an object, with position on the vertical axis and time on the horizontal axis. **Figure 2** shows a position–time graph for the motion of a rolling ball measured by students during an experiment. Notice that the points on the graph form a straight line that moves upward from left to right. Whenever an object is moving at a constant velocity, the position–time graph of that motion is a straight line.

slope (m) a measure of the steepness of a line

rise vertical change between two points on a line

run horizontal change between two points on a line

You may recall from your mathematics studies that the **slope** of a line describes its steepness. The symbol for slope is m. Slope is determined, as shown in Figure 2, by comparing the magnitude of the **rise** (the change between points on the y-axis) and the magnitude of the **run** (the change between the same points on the x-axis). You can use this technique whether the graph passes through the origin or not; for example, in **Figure 3** the motion begins at a position of 10 m [E] when $t = 0$ s.

For an object moving at a constant velocity, so that its position–time graph is a straight line, the key relationship is this:

The slope of a position–time graph gives the velocity of the object.

The steeper the graph, the greater is the object's displacement in a given time interval, and the higher is its velocity. This can be confirmed using the information in Figure 2. Since the y-axis shows change in position, $\Delta\vec{d}$, and the x-axis shows change in time, Δt, the formula for the slope of this graph can be rewritten as follows:

$$\text{slope} = \frac{\text{rise}}{\text{run}}$$

$$m = \frac{\vec{d}_2 - \vec{d}_1}{t_2 - t_1}$$

$$\text{or} \quad m = \frac{\Delta\vec{d}}{\Delta t}$$

LEARNING TIP

Rates of Change

Average speed and average velocity are examples of rates of change—an important concept in science that describes how quickly a quantity is changing. Velocity is the rate of change of position, which means that the more rapidly an object's position is changing, the greater is the magnitude of its velocity.

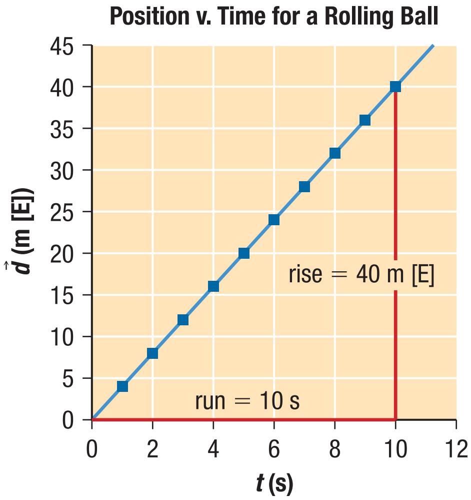


Figure 2 Calculating the slope of a position–time graph

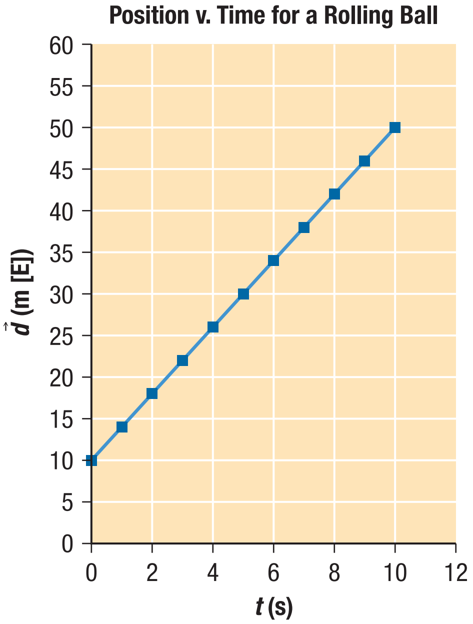


Figure 3 A position–time graph with non-zero initial position

The (average) velocity of a moving object is given by the equation

$$\vec{v}_{\text{av}} = \frac{\Delta \vec{d}}{\Delta t}$$

To determine the slope—the average velocity—from the zero point to the final data point for the *x*-axis and *y*-axis for the motion shown in Figure 2, substitute the initial and final displacement and time values into the equation we just derived:

$$\begin{aligned}\vec{v}_{\text{av}} &= \frac{\Delta \vec{d}}{\Delta t}\\ m &= \frac{\vec{d}_2 - \vec{d}_1}{t_2 - t_1}\\ &= \frac{40\text{ m [E]} - 0\text{ m}}{10\text{ s} - 0\text{ s}}\\ m &= 4\text{ m/s [E]}\end{aligned}$$

The velocity of the rolling ball is 4 m/s [E]. Note that the slopes of the graphs shown in Figure 2 and Figure 3 are the same, 4 m/s [E]. The two motions are different in that the motion described by Figure 2 started 0 m away from the observer, whereas the motion graphed in Figure 3 had an initial position of 10 m [E] from the observer. Calculating average velocity from the slope of a position–time graph is a very useful technique because average velocity is often difficult to measure directly. However, position can be easily measured with equipment such as tape measures, motion sensors, and laser speed devices.

Velocity (a vector quantity) is to speed (a scalar quantity) as displacement (a vector quantity) is to distance (a scalar quantity). The equation for average velocity should therefore look similar to the equation for average speed, except that velocity and displacement are vectors:

$$\vec{v}_{\text{av}} = \frac{\Delta \vec{d}}{\Delta t}$$

where $\Delta \vec{d}$ is the change in position and Δt is the change in time during the given time interval. This is the same equation as the one we just derived using the slope of a position–time graph.

Note that Δt can also be described by the equation $\Delta t = t_2 - t_1$. Often, we can simplify this equation by considering t_1, the start time, to be 0 s. In the following Tutorial, we will use the average velocity equation to determine unknown values.

LEARNING **TIP**

Calculations with Vectors

In general, you cannot divide one vector by another, as dividing a direction has no meaning. However, if the directions of both vectors are the same, you can disregard the direction and divide one magnitude by the other.

Tutorial 2 Solving Problems Using the Equation for Average Velocity

The equation for average velocity can be used to solve for any of the three variables in the average velocity equation when the other two are known. In the following Sample Problems, we will review solving equations for an unknown variable using the equation for average velocity.

Sample Problem 1: Calculating the Average Velocity of an Object

On a windy day, the position of a balloon changes as it is blown 82 m [N] away from a child in 15 s. What is the average velocity of the balloon?

Solution

We are given the change in time and the change in position of the balloon, so we can solve for average velocity.

Given: $\Delta \vec{d} = 82\text{ m [N]}$; $\Delta t = 15\text{ s}$

Required: $\vec{v}_{\text{av}}$

Analysis: $\vec{v}_{\text{av}} = \dfrac{\Delta \vec{d}}{\Delta t}$

Solution:
$$\begin{aligned}\vec{v}_{\text{av}} &= \frac{\Delta \vec{d}}{\Delta t}\\ &= \frac{82\text{ m [N]}}{15\text{ s}}\\ \vec{v}_{\text{av}} &= 5.5\text{ m/s [N]}\end{aligned}$$

Statement: The average velocity of the balloon is 5.5 m/s [N].

Sample Problem 2: Calculating the Time for a Displacement to Occur

A subway train travels at an average velocity of 22.3 km/h [W]. How long will it take for the subway train to undergo a displacement of 241 m [W]?

Given: $\vec{v}_{\text{av}} = 22.3\ \text{km/h}\ [\text{W}];\ \Delta\vec{d} = 241\ \text{m}\ [\text{W}]$

Required: Δt

Analysis: $\vec{v}_{\text{av}} = \dfrac{\Delta\vec{d}}{\Delta t}$

Since we are given the average velocity and the displacement of the subway train, we can rearrange the average velocity equation to solve for the change in time.

Solution: Before we solve this problem, we must first make sure that all of the given values are converted to SI metric units. This will require us to convert 22.3 km/h to metres per second. We will do this by multiplying 22.3 km/h by a series of ratios equal to 1. We will use these ratios so that the units that we do not want (kilometres and hours) will cancel, and we will be left with the units we do want (metres and seconds).

$$\vec{v}_{\text{av}} = \left(22.3\,\frac{\cancel{\text{km}}}{\cancel{\text{h}}}\,[\text{W}]\right)\left(\frac{1\,\cancel{\text{h}}}{60\,\cancel{\text{min}}}\right)\left(\frac{1\,\cancel{\text{min}}}{60\ \text{s}}\right)\left(\frac{1000\ \text{m}}{1\,\cancel{\text{km}}}\right)$$

$$= \left(\frac{22.3\,[\text{W}] \times 1000\ \text{m}}{60 \times 60\ \text{s}}\right)$$

$$\vec{v}_{\text{av}} = 6.1944\ \text{m/s}\ [\text{W}]\ \text{(two extra digits carried)}$$

Now that we have converted units, we can use the average velocity equation to determine the change in time.

$$\vec{v}_{\text{av}} = \frac{\Delta\vec{d}}{\Delta t}$$

$$\Delta t = \frac{\Delta\vec{d}}{\vec{v}_{\text{av}}}$$

$$= \frac{241\ \text{m}\ [\text{W}]}{6.1944\ \text{m/s}\ [\text{W}]}$$

$$\Delta t = 38.9\ \text{s}$$

Statement: It takes the subway train 38.9 s to be displaced 241 m [W] from its starting point.

Practice

1. What is the average velocity of a soccer ball that is kicked and travels 2.17 m [E] in 1.36 s? T/I [ans: 1.60 m/s [E]]
2. How long will it take a cat to run 8.2 m [N] at an average velocity of 3.7 m/s [N]? T/I [ans: 2.2 s]

Motion with Uniform and Non-uniform Velocity

Motion with uniform or constant velocity is motion at a constant speed in a straight line. It is the simplest type of motion that an object can undergo, except for being at rest. Note that both requirements (constant speed and straight line) must be met for an object's velocity to be uniform. In contrast, **motion with non-uniform velocity** is motion that is not at a constant speed or not in a straight line. Motion with non-uniform velocity may also be called **accelerated motion**. **Table 1** shows some examples of motion with uniform velocity. You will learn more about accelerated motion in Section 1.3.

motion with uniform or constant velocity motion of an object at a constant speed in a straight line

motion with non-uniform velocity (accelerated motion) motion in which the object's speed changes or the object does not travel in a straight line

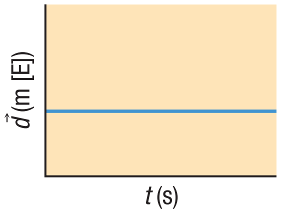
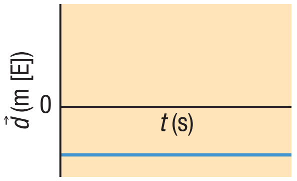
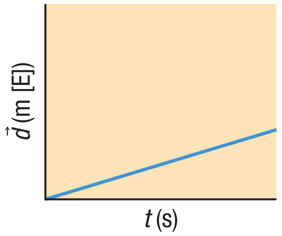
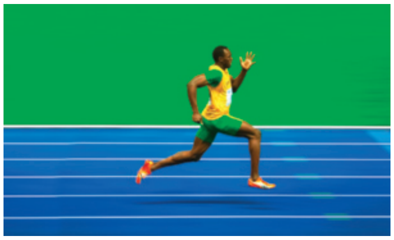
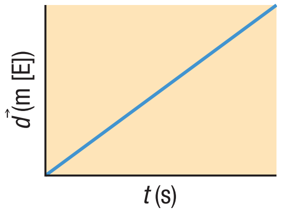
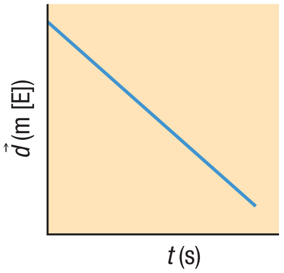
Table 1 Examples of Uniform and Non-uniform Velocity

Example	Uniform velocity	Non-uniform velocity	Explanation
A car travels down a straight highway at a steady 100 km/h.	✓		The car is travelling at a constant speed in a straight line.
A passenger on an amusement park ride travels in a circle at a constant speed of 1.2 m/s.		✓	The passenger is travelling at a constant speed but not in a straight line. She is travelling in a circle.
A parachutist jumps out of an aircraft.	✓ (after parachute opens)	✓ (before parachute opens)	Before he opens the parachute, the speed of the parachutist will increase due to gravity. Once the parachute is opened, his speed will become constant due to air resistance. He will then fall at a constant speed in the same direction (downwards).

Determining Types of Motion from Position–Time Graphs

Recall that the slope of a position–time graph gives the velocity of an object. A position–time graph that describes constant velocity must be a straight line because motion with constant velocity is motion at a constant speed. Therefore, the slope of the position–time graph must also be constant. **Table 2** shows five position–time graphs that represent commonly occurring types of motion. You will see these types of motion frequently in investigations. By the end of this unit, you should be able to identify the type of motion from the characteristics of its position–time graph.

Table 2 Interpreting Position–Time Graphs

Position–time graph	Type of motion	Example
Graph A 	• graph is a horizontal straight line • the slope of a horizontal straight line is zero • the object has a velocity of zero • the object is ***at rest*** • the object is at a constant positive position relative to the reference position • the object is stationary at a location to the east of the reference position	
Graph B 	• graph is a horizontal straight line • the slope of a horizontal straight line is zero • the object has a velocity of zero • the object is ***at rest*** • the object is at a constant negative position relative to the reference position • the object is stationary at a location to the west of the reference position	
Graph C 	• graph is a straight line with positive slope • straight lines with non-zero slopes always represent ***constant*** **(non-zero)** ***velocity*** • from the *y*-axis, we know the object is moving eastward • the object's velocity can be determined from the slope of the graph (rise divided by run)	
Graph D 	• graph is a straight line with positive slope, which represents ***constant*** **(positive)** ***velocity*** • from the *y*-axis, we know the object is moving eastward • the object's velocity can be determined from the slope of the graph • since graph D has the steeper slope, we can conclude that this object has a greater velocity than the object described by graph C	
Graph E 	• graph is a straight line, which represents ***constant velocity*** • the slope of the graph is negative • the object's velocity can be determined from the slope of the graph • note that the direction for position on the *y*-axis is given by a vector with direction [E] • the negative slope indicates that the object is moving westward	

Mini Investigation

Bodies in Motion

Skills: Performing, Observing, Analyzing SKILLS HANDBOOK A6.2

Motion sensors are devices that send out ultrasonic wave pulses. When some of these waves reflect off an object, the waves return to the motion sensor. A computer can then analyze the data from the returning waves and generate real-time position–time graphs. Using motion sensors can help you understand position–time graphs.

Equipment and Materials: motion sensor; computer or computer interface; graph paper; pencil

1. Connect the motion sensor to a computer or computer interface.
2. Place the motion sensor on a lab bench. Make sure that you have about 4 m of free space in front of the motion sensor.
3. You will be using your body to generate position–time data with the motion sensor. Before you begin, sketch position–time graphs to show the overall shape and features of the graphs that you predict the motion sensor will generate for each of the following scenarios:
   - slow constant speed
   - fast constant speed
   - speeding up
   - slowing down
4. Using the motion sensor, generate real-time position–time graphs for each scenario in Step 3 using body motions.

A. Compare your predictions with the results. Explain any differences. T/I C

B. If there is time, use the motion sensor to generate graphs that resemble as many letters of the alphabet as you can. T/I C

1.2 Summary

- Average speed is equal to the total distance travelled divided by the time taken for the motion.
- A position–time graph describes motion graphically. The slope of the position–time graph gives the velocity of an object.
- Average velocity is equal to the total displacement divided by the time taken for the motion. In other words, velocity describes change in position over time.
- Motion with uniform or constant velocity is motion at a constant speed in a straight line.
- Objects that are undergoing constant velocity have a position–time graph that is a straight line.

1.2 Questions

1. When you are solving a problem, how do you know if you are given a speed value or a velocity value? K/U
2. Define motion with uniform velocity in your own words. K/U C
3. Give two real-life examples each of motion with uniform velocity and motion with non-uniform velocity. A
4. Determine the velocity for the motion described by the graph in **Figure 4**. T/I

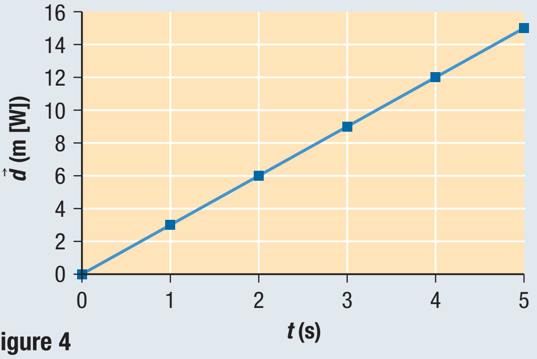


Figure 4

5. Copy and complete **Table 3** in your notebook. T/I

Table 3

$\vec{v}_{av}$	$\Delta\vec{d}$	Δt
	12.6 m [S]	16.3 s
2.0×10^3 m/s [E]	25 m [E]	
40 m/s [N]		0.25 s

6. What is the displacement of a horse that runs at a velocity of 3.2 m/s [S] for 12 s? T/I
7. How many seconds would it take a car travelling at 100.0 km/h to travel a distance of 16 m? T/I
8. What is the velocity (in metres per second) of a Canadian Forces CF-18 fighter jet that travels 8.864 km [S] in 0.297 min? T/I

1.3

Acceleration

Some theme parks have rides in which you are slowly carried up in a seat to the top of a tower, and then suddenly released **(Figure 1)**. On the way down, your arms and hair may fly upward as the velocity of your seat increases. The thrill of this sudden change in motion can frighten and exhilarate you all at once. An even bigger thrill ride, however, is to be a pilot in a jet being launched from the deck of an aircraft carrier. These giant ships use catapults to move 35 000 kg jets from rest (0 km/h) to 250 km/h in just 2.5 s.

While it is true that objects sometimes move at constant velocity in everyday life, usually the velocities we observe are not constant. Objects that experience a change in velocity are said to be undergoing acceleration. **Acceleration** describes how quickly an object's velocity changes over time or the rate of change of velocity. We can study acceleration using a **velocity–time graph**, which, similar to the position–time graph, has time on the horizontal axis, but velocity rather than position on the vertical axis.

Velocity–time graphs are particularly useful when studying objects moving with uniform velocity (zero acceleration) or uniform acceleration (velocity changing, but at a constant rate). The velocity–time graphs for both uniform velocity and uniform acceleration are always straight lines. By contrast, the position–time graph of an accelerated motion is curved. **Table 1** shows the position–time graphs of objects moving with accelerated motion.

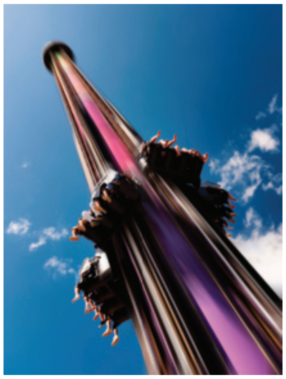


Figure 1 Sudden changes in velocity are part of the thrill of midway rides.

acceleration ($\vec{a}_{av}$) how quickly an object's velocity changes over time (rate of change of velocity)

velocity–time graph a graph describing the motion of an object, with velocity on the vertical axis and time on the horizontal axis

Table 1 Interpreting Position–Time Graphs

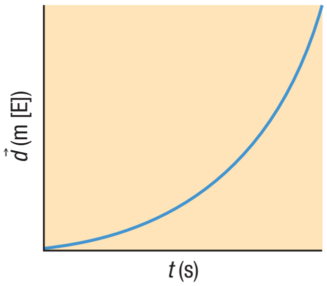
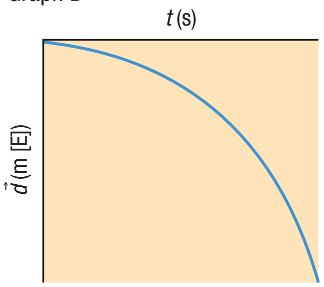
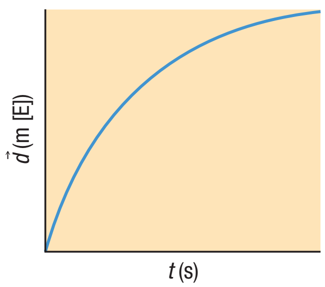
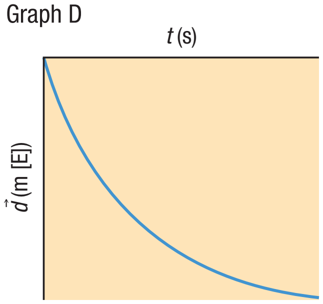
Position–time graph	Type of motion	Example
Graph A  	• graph is a curve • on any graph that curves, the slope or steepness of the graph changes from one point on the graph to another • since the slope in graph A is constantly changing, the velocity is not constant • since the graph lies above the *x*-axis and its slope is increasing, the velocity of the object is also increasing (***speeding up***) in a positive or eastward direction	
Graph B  	• graph is a curve • on any graph that curves, the slope or steepness of the graph changes from one point on the graph to another • since the slope in graph B is constantly changing, the velocity is not constant • since the graph lies below the *x*-axis and its slope is negative but getting steeper, the object is ***speeding up*** as it moves in a negative or westward direction	

Table 1 (continued)

Position–time graph	Type of motion	Example
Graph C 	- graph is a curve - on any graph that curves, the slope changes from one point on the curve to another - since the slope in graph C is constantly changing, the velocity is not constant - since the graph lies above the *x*-axis and its slope is decreasing, the velocity of the object is also decreasing (***slowing down***) in a positive or eastward direction	
Graph D 	- graph is a curve - on any graph that curves, the slope or steepness of the graph changes from one point on the graph to another - since the slope in graph D is constantly changing, the velocity is not constant - since the graph lies below the *x*-axis and its slope is negative and getting shallower, the object is ***slowing down*** as it moves in a negative or westward direction	

Determining Acceleration from a Velocity–Time Graph

Figure 2 shows a velocity–time graph for a skateboard rolling down a ramp. Notice that the line of the graph goes upward to the right and has *x*-intercept and *y*-intercept of zero. We can calculate the slope of the graph in Figure 2 using the equation

$$\text{slope} = \frac{\text{rise}}{\text{run}}$$

$$m = \frac{\Delta\vec{v}\ (\text{m/s})}{\Delta t\ (\text{s})}$$

Since acceleration describes change in velocity over time, this suggests that the (average) acceleration of the skateboard is given by the equation

$$\vec{a}_{\text{av}} = \frac{\Delta\vec{v}}{\Delta t}$$

LEARNING **TIP**

Slope and Area of Velocity–Time Graphs

The slope of a velocity–time graph gives the acceleration of the object. The area under a velocity–time graph gives the displacement of the object. Why is displacement related to the area under a velocity–time graph? One way to think about it is this: the greater the velocity during a given time interval, the greater the area under the graph, and the greater the displacement over that time interval.

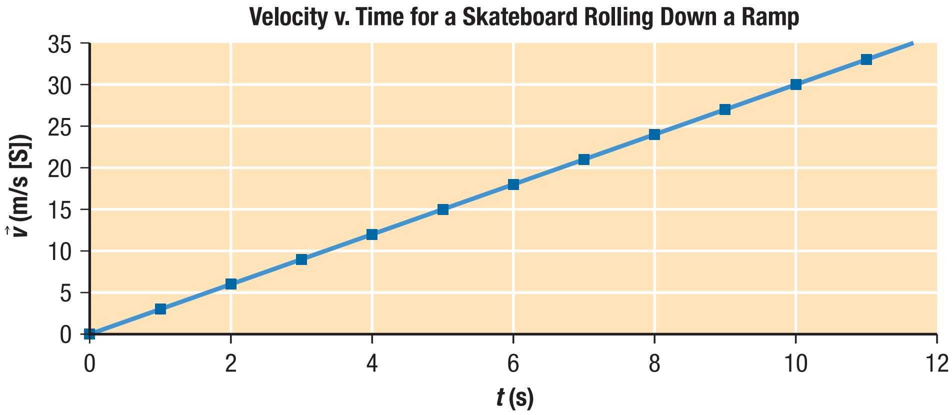


Figure 2 Velocity–time graph for a skateboard rolling down a ramp

In other words,

The slope of a velocity–time graph gives the average acceleration of an object.

Acceleration over a time interval, that is, average acceleration, is given by the equation

$$\text{average acceleration} = \frac{\text{change in velocity}}{\text{change in time}}$$

$$\vec{a}_{\text{av}} = \frac{\Delta\vec{v}}{\Delta t}$$

$$\text{or } \vec{a}_{\text{av}} = \frac{\vec{v}_{\text{f}} - \vec{v}_{\text{i}}}{\Delta t}$$

Recall that the SI unit for velocity is metres per second (m/s) and the SI unit for time is seconds (s). The SI unit for acceleration is a derived unit. A derived SI unit is a unit created by combining SI base units. We can derive the units for acceleration by dividing a velocity unit (m/s) by a time unit (s), as follows:

$$\begin{aligned}\text{units of acceleration} &= \text{units of velocity per second}\\ &= \frac{\frac{\text{m}}{\text{s}}}{\text{s}}\\ &= \frac{\text{m}}{\text{s}} \times \frac{1}{\text{s}}\\ &= \frac{\text{m}}{\text{s}^2}\end{aligned}$$

LEARNING **TIP**

Square Seconds?
What is a square second? Good question! When we write acceleration units as m/s^2, we are not implying that we have measured a square second. This is simply a shorter way of expressing the derived unit. You can also read the unit as "metres per second, per second"—describing how many metres per second of velocity are gained or lost during each second of acceleration.

Tutorial 1 Calculating Acceleration

When you are given values for any three variables in the equation $\vec{a}_{\text{av}} = \frac{\vec{v}_{\text{f}} - \vec{v}_{\text{i}}}{\Delta t}$ for acceleration, you can solve for the missing variable.

Sample Problem 1

What is the acceleration of the skateboard in Figure 2? Consider the motion between 0 s and 10 s.

Given: $\vec{v}_{\text{i}} = 0\ \text{m/s}$; $\vec{v}_{\text{f}} = 30\ \text{m/s [S]}$; $t_{\text{i}} = 0\ \text{s}$; $t_{\text{f}} = 10\ \text{s}$

Required: $\vec{a}_{\text{av}}$

Analysis: To calculate the average acceleration, which is the slope of the graph, we use the defining equation in the form that includes $\vec{v}_{\text{i}}$, $\vec{v}_{\text{f}}$, t_{i}, and t_{f}:

$$\begin{aligned}\vec{a}_{\text{av}} &= \frac{\Delta\vec{v}}{\Delta t}\\ &= \frac{\vec{v}_{\text{f}} - \vec{v}_{\text{i}}}{t_{\text{f}} - t_{\text{i}}}\end{aligned}$$

Solution:
$$\begin{aligned}\vec{a}_{\text{av}} &= \frac{\vec{v}_{\text{f}} - \vec{v}_{\text{i}}}{t_{\text{f}} - t_{\text{i}}}\\ &= \frac{30\ \text{m/s [S]} - 0\ \text{m/s}}{10\ \text{s} - 0\ \text{s}}\\ \vec{a}_{\text{av}} &= 3\ \text{m/s}^2\ \text{[S]}\end{aligned}$$

Statement: The skateboard is accelerating down the ramp at $3\ \text{m/s}^2$ [S].

What would the acceleration be if the same velocity change of 30 m/s [S] took place over a time interval of only 5 s?

$$\begin{aligned}\vec{a}_{\text{av}} &= \frac{\Delta\vec{v}}{\Delta t}\\ &= \frac{30\ \text{m/s [S]}}{5\ \text{s}}\\ \vec{a}_{\text{av}} &= 6\ \text{m/s}^2\ \text{[S]}\end{aligned}$$

The time interval is shorter, so a more rapid acceleration occurs.

Sample Problem 2

A bullet is found lodged deeply in a brick wall. As part of the investigation, a forensic scientist is experimenting with a rifle that was found nearby. She needs to determine the acceleration that a bullet from the rifle can achieve as a first step in linking the rifle to the bullet. During a test firing, she finds that the rifle bullet accelerates from rest to 120 m/s [E] in 1.3×10^{-2} s as it travels down the rifle's barrel. What is the bullet's average acceleration?

Given: $\vec{v}_\mathrm{i} = 0\ \mathrm{m/s}$; $\vec{v}_\mathrm{f} = 120\ \mathrm{m/s}\ [\mathrm{E}]$; $\Delta t = 1.3 \times 10^{-2}\ \mathrm{s}$

Required: $\vec{a}_\mathrm{av}$

Analysis: $\vec{a}_\mathrm{av} = \dfrac{\vec{v}_\mathrm{f} - \vec{v}_\mathrm{i}}{\Delta t}$

Solution: $\vec{a}_\mathrm{av} = \dfrac{\vec{v}_\mathrm{f} - \vec{v}_\mathrm{i}}{\Delta t}$

$$= \frac{120\,\dfrac{\mathrm{m}}{\mathrm{s}}\,[\mathrm{E}] - 0\,\dfrac{\mathrm{m}}{\mathrm{s}}}{1.3 \times 10^{-2}\ \mathrm{s}}$$

$$\vec{a}_\mathrm{av} = 9.2 \times 10^{3}\ \mathrm{m/s^2}\ [\mathrm{E}]$$

Statement: The acceleration of the bullet is $9.2 \times 10^{3}\ \mathrm{m/s^2}$ [E].

Sample Problem 3

When a hockey player hits a hockey puck with his stick, the velocity of the puck changes from 8.0 m/s [N] to 10.0 m/s [S] over a time interval of 0.050 s. What is the acceleration of the puck?

Given: $\vec{v}_\mathrm{i} = 8.0\ \mathrm{m/s}\ [\mathrm{N}]$; $\vec{v}_\mathrm{f} = 10.0\ \mathrm{m/s}\ [\mathrm{S}]$; $\Delta t = 0.050\ \mathrm{s}$

Required: $\vec{a}_\mathrm{av}$

Analysis: $\vec{a}_\mathrm{av} = \dfrac{\vec{v}_\mathrm{f} - \vec{v}_\mathrm{i}}{\Delta t}$

Solution: $\vec{a}_\mathrm{av} = \dfrac{\vec{v}_\mathrm{f} - \vec{v}_\mathrm{i}}{\Delta t}$

$$\vec{a}_\mathrm{av} = \frac{10.0\ \mathrm{m/s}\ [\mathrm{S}] - 8.0\ \mathrm{m/s}\ [\mathrm{N}]}{0.050\ \mathrm{s}}$$

At this point, it would appear that we have a dilemma. In the numerator of the fraction, we must subtract a vector with a direction [N] from a vector with a direction [S].

To solve this dilemma, we can use a technique from Section 1.2. We will change a vector subtraction problem into a vector addition problem. Recall that negative [N] is the same as positive [S].

$$\vec{a}_\mathrm{av} = \frac{10.0\ \mathrm{m/s}\ [\mathrm{S}] + 8.0\ \mathrm{m/s}\ [\mathrm{S}]}{0.050\ \mathrm{s}}$$

$$= \frac{18.0\ \mathrm{m/s}\ [\mathrm{S}]}{0.050\ \mathrm{s}}$$

$$\vec{a}_\mathrm{av} = 3.6 \times 10^{2}\ \mathrm{m/s^2}\ [\mathrm{S}]$$

Statement: The hockey puck's acceleration is $3.6 \times 10^{2}\ \mathrm{m/s^2}$ [S].

Notice that the initial velocity of the puck is north, while its final velocity is south. The acceleration is in the opposite direction to the initial motion, so the puck slows down and comes to rest. It then continues accelerating south, increasing its velocity to 10 m/s [S]. This is why the final velocity is due south. Sample Problem 3 can also be solved by using a vector scale diagram.

Practice

1. A catapult accelerates a rock from rest to a velocity of 15.0 m/s [S] over a time interval of 12.5 s. What is the rock's average acceleration? T/I [ans: 1.20 $\mathrm{m/s^2}$ [S]]
2. As a car approaches a highway on-ramp, it increases its velocity from 17 m/s [N] to 25 m/s [N] over 12 s. What is the car's average acceleration? T/I [ans: 0.67 $\mathrm{m/s^2}$ [N]]
3. A squash ball with an initial velocity of 25 m/s [W] is hit by a squash racket, changing its velocity to 29 m/s [E] in 0.25 s. What is the squash ball's average acceleration? T/I [ans: $2.2 \times 10^{2}\ \mathrm{m/s^2}$ [E]]

You can use both the defining equation for average acceleration and velocity–time graphs to determine other information about the motion of an object, besides acceleration itself. In Tutorial 2, you will use the equation in a different form to determine a different quantity. Tutorial 3 introduces the idea of determining displacement via the area under a velocity–time graph.

Tutorial 2 Solving the Acceleration Equation for Other Variables

In the following Sample Problem, we will explore how to solve the defining acceleration equation for other variables.

Sample Problem 1: Solving the Acceleration Equation for Final Velocity

A racehorse takes 2.70 s to accelerate from a trot to a gallop. If the horse's initial velocity is 3.61 m/s [W] and it experiences an acceleration of 2.77 m/s² [W], what is the racehorse's velocity when it gallops?

Given: $\Delta t = 2.70\text{ s}$; $\vec{v}_i = 3.61\text{ m/s [W]}$; $\vec{a}_{av} = 2.77\text{ m/s}^2\text{ [W]}$

Required: $\vec{v}_f$

Analysis: $\vec{a}_{av} = \dfrac{\vec{v}_f - \vec{v}_i}{\Delta t}$

Solution: Rearrange the equation for acceleration to solve for the final velocity.

$$\vec{a}_{av}\,\Delta t = \vec{v}_f - \vec{v}_i$$

$$\vec{v}_f = \vec{a}_{av}\,\Delta t + \vec{v}_i$$

$$= \left(2.77\,\frac{\text{m}}{\text{s}^{\cancel{2}}}\,[\text{W}]\right)(2.70\,\cancel{\text{s}}) + 3.61\,\frac{\text{m}}{\text{s}}\,[\text{W}]$$

$$= 7.48\text{ m/s [W]} + 3.61\text{ m/s [W]}$$

$$\vec{v}_f = 11.1\text{ m/s [W]}$$

Statement: When it gallops, the racehorse has a velocity of 11.1 m/s [W].

Practice

1. How long does it take a radio-controlled car to accelerate from 3.2 m/s [W] to 5.8 m/s [W] if it experiences an average acceleration of 1.23 m/s² [W]? T/I [ans: 2.1 s]
2. A speedboat experiences an average acceleration of 2.4 m/s² [W]. If the boat accelerates for 6.2 s and has a final velocity of 17 m/s [W], what was the initial velocity of the speedboat? T/I [ans: 2.1 m/s [W]]

Tutorial 3 Determining Displacement from a Velocity–Time Graph

By further analyzing the velocity–time graph shown in Figure 2 on page 22, we can determine even more information about the motion of the skateboard. **Figure 3** has the same data plotted as Figure 2, except that the area under the line is shaded. The area under a velocity–time graph gives the displacement of the object. Note how the area under the straight line in Figure 3 forms a triangle. The area (A) of a triangle is determined by the equation

$$A = \frac{1}{2}bh$$

$$\Delta\vec{d} = \frac{1}{2}bh$$

where b is the length of the base of the triangle and h is the height of the triangle. We can determine the displacement of the skateboard from Figure 3 by calculating the area of this triangle.

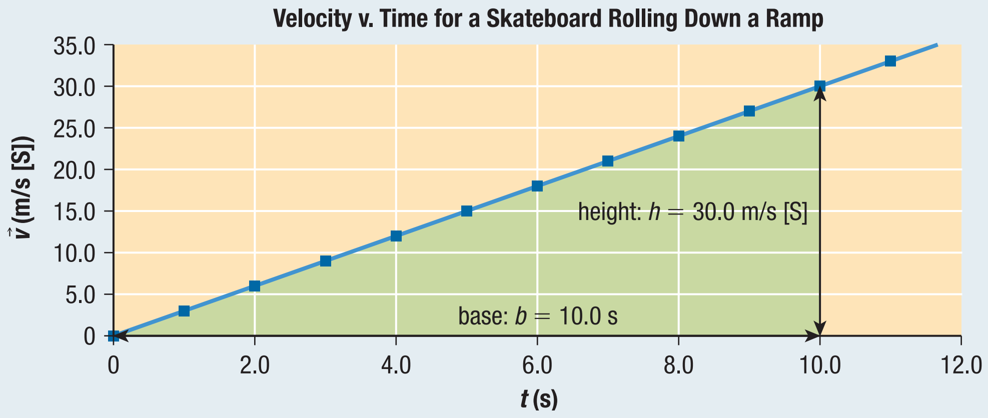


Figure 3 Velocity–time graph showing the area underneath the line

Sample Problem 1: Determining Displacement from a Velocity–Time Graph

What is the displacement represented by the graph in Figure 3 on the previous page?

Given: $b = 10.0$ s; $h = 30.0$ m/s [S]

Required: $\Delta\vec{d}$

Analysis: $\Delta\vec{d} = \frac{1}{2}bh$

Solution: $\Delta\vec{d} = \frac{1}{2}(10.0\ \cancel{s})\left(30.0\ \frac{\text{m}}{\cancel{\text{s}}}\ [\text{S}]\right)$

$$\Delta\vec{d} = 150\ \text{m}\ [\text{S}]$$

Statement: The object was displaced 150 m [S] in 10 s.

Sample Problem 2: Determining Displacement from a More Complex Velocity–Time Graph

What is the displacement represented by the graph in **Figure 4** over the time interval from 0 s to 10.0 s?

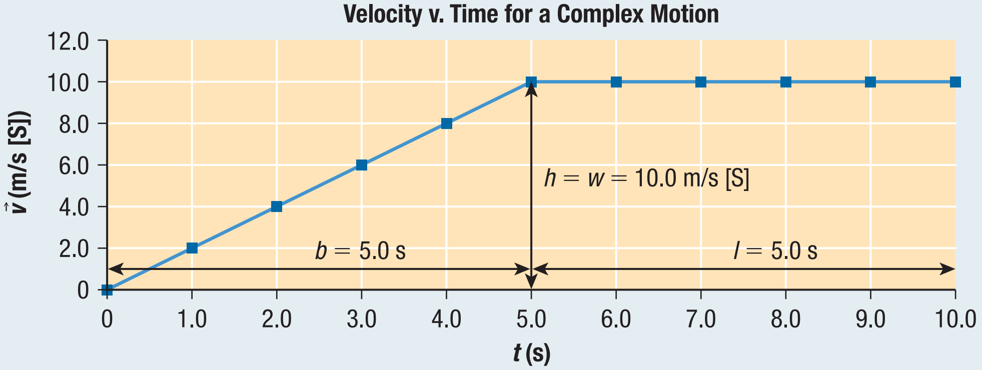


Figure 4 Velocity–time graph showing more complex motion

The graph in Figure 4 is a more complex velocity–time graph than we worked with in Sample Problem 1. However, the displacement of the object can still be determined by calculating the area under the velocity–time graph.

To calculate this displacement, we will need to break the area under the line into a rectangle and a triangle, and add these two areas together. We know the area (A) of a triangle is given by $A_{\text{triangle}} = \frac{1}{2}bh$. The area of a rectangle is its length (l) multiplied by its width (w), or $A_{\text{rectangle}} = lw$.

Given: $b = 5.0$ s; $h = 10.0$ m/s [S]; $l = 5.0$ s; $w = 10.0$ m/s [S]

Required: $\Delta\vec{d}$

Analysis: $\Delta\vec{d} = A_{\text{triangle}} + A_{\text{rectangle}}$

Solution: $\Delta\vec{d} = A_{\text{triangle}} + A_{\text{rectangle}}$

$$
\begin{aligned}
&= \frac{1}{2}bh + lw \\
&= \frac{1}{2}(5.0\ \cancel{s})\left(10.0\ \frac{\text{m}}{\cancel{\text{s}}}\ [\text{S}]\right) + (5.0\ \cancel{s})\left(10.0\ \frac{\text{m}}{\cancel{\text{s}}}\ [\text{S}]\right) \\
&= 25\ \text{m}\ [\text{S}] + 50.0\ \text{m}\ [\text{S}]
\end{aligned}
$$

$$\Delta\vec{d} = 75\ \text{m}\ [\text{S}]$$

Statement: The object has travelled 75 m [S] after 10.0 s.

Practice

1. Determine the displacement represented by the graph in Figure 4 over the following time intervals: T/I
   (a) from 0 s to 4.0 s [ans: 16 m [S]]
   (b) from 0 s to 7.5 s [ans: 50 m [S]]

Mini Investigation

Motion Simulations

Skills: Predicting, Performing, Observing, Analyzing, Communicating SKILLS HANDBOOK A2.1

In this investigation, you will use a computer simulation for four different motion scenarios and then analyze the scenarios by graphing.

Equipment and Materials: computer access; graphing paper

1. Go to the Nelson website and find the link for this Mini Investigation.
2. Go to the simulation, and take a few minutes to familiarize yourself with how it operates. You will be asked to run this simulation for each of the following scenarios:
   - a positive velocity value
   - a negative velocity value
   - a negative initial position and a positive velocity value
   - a negative initial position and a negative velocity value

A. Before you run these scenarios, write a brief statement and draw a sketch to predict how each graph will appear. T/I C

B. After you have run each scenario, sketch the resulting position–time and velocity–time graphs from the actual data you collected. T/I C

C. Compare your sketches from Question A to the graphs that were generated when you ran each scenario. Explain any discrepancies or misconceptions that you may have had. T/I

GO TO NELSON SCIENCE

Figure 5 Launch of NASA's Mars Pathfinder mission

Instantaneous Velocity and Average Velocity

The velocity of any object that is accelerating is changing over time. In **motion with uniform acceleration**, the velocity of an object changes at a constant (uniform) rate. During a launch (**Figure 5**), a spacecraft accelerates upward at a rapid rate. NASA personnel may need to determine the velocity of the spacecraft at specific points in time. They can do this by plotting position and time data on a graph and determining the spacecraft's instantaneous velocity. **Instantaneous velocity**, or $\vec{v}_{\text{inst}}$, is the velocity of an object at a specific instant in time. By comparison, average velocity ($\vec{v}_{\text{av}}$) is determined over a time *interval*. Both types of velocity are rates of change of position, but they tell us different things about the motion of an object.

motion with uniform acceleration motion in which velocity changes at a constant rate

instantaneous velocity ($\vec{v}_{\text{inst}}$) the velocity of an object at a specific instant in time

Tutorial 4 Determining Instantaneous and Average Velocity

Figure 6 on the next page shows a position–time graph of an object that is undergoing uniform acceleration. Moving along the curve, the slope of the curve progressively increases. From this, we know that the velocity of the object is constantly increasing.

To determine the instantaneous velocity of the object at a specific time, we must calculate the slope of the tangent of the line on the position–time graph at that time. A tangent is a straight line that contacts a curve at a single point and extends in the same direction as the slope of the curve at the point.

A plane mirror can be used to draw a tangent to a curved line. Place the mirror as perpendicular as possible to the line at the point desired. Adjust the angle of the mirror so that the real curve merges smoothly with its image in the mirror, which will occur when the mirror is perpendicular to the curved line at that point. Draw a line perpendicular to the mirror to obtain the tangent to the curve.

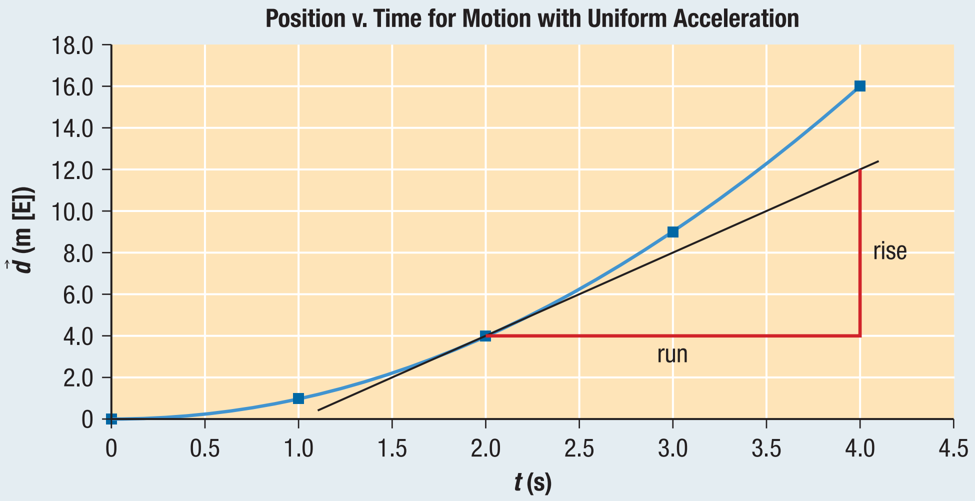


Figure 6 Position–time graph with non-constant velocity

We can use Figure 6 to determine the instantaneous velocity of the object at any specific point in time. To determine the instantaneous velocity, we must determine the slope of the tangent of the line on the position–time graph at that specific time.

Sample Problem 1: Determining Instantaneous Velocity

Consider the point on the curve in Figure 6 at 2.0 s on the *x*-axis. What is the instantaneous velocity of the object at this time?

Given: $t = 2.0$ s; position–time graph

Required: $\vec{v}_{\text{inst}}$

Analysis: $\vec{v}_{\text{inst}}$ is equal to the slope, m, of the tangent to the curve at $t = 2.0$ s, so $m = \frac{\Delta\vec{d}}{\Delta t}$

In Figure 6, the tangent to the point on the curve at $t = 2.0$ s has been extended until it crosses a convenient grid line. Calculate the slope of the tangent to determine the instantaneous velocity.

Solution: $m = \frac{8.0 \text{ m [E]}}{2.0 \text{ s}}$

$$\vec{v}_{\text{inst}} = 4.0 \text{ m/s [E]}$$

Statement: The instantaneous velocity of the object at 2.0 s is 4.0 m/s [E].

Since the object is accelerating, if we had calculated the slope of the tangent at time $t = 1.0$ s, the velocity would have been smaller in magnitude, and if we had calculated the slope of the tangent at time $t = 3.0$ s, the velocity would have been greater. We can also use Figure 6 to determine the average velocity of the object.

Sample Problem 2: Determining Average Velocity from a Position–Time Graph

What is the average velocity of the object in Figure 6 over the time interval from 0.0 s to 2.0 s?

Given: $\vec{d}_1 = 0.0$ m; $\vec{d}_2 = 4.0$ m [E]; $t_1 = 0.0$ s; $t_2 = 2.0$ s

Required: $\vec{v}_{\text{av}}$

Analysis: Recall that average velocity is the total displacement of an object divided by the total time taken.

$$\vec{v}_{\text{av}} = \frac{\Delta\vec{d}}{\Delta t}$$

$$\vec{v}_{\text{av}} = \frac{\vec{d}_2 - \vec{d}_1}{t_2 - t_1}$$

Solution: $\vec{v}_{\text{av}} = \frac{\vec{d}_2 - \vec{d}_1}{t_2 - t_1}$

$$= \frac{4.0 \text{ m [E]} - 0.0 \text{ m}}{2.0 \text{ s} - 0.0 \text{ s}}$$

$$\vec{v}_{\text{av}} = 2.0 \text{ m/s [E]}$$

Statement: The average velocity of the object over the time interval from 0.0 s to 2.0 s is 2.0 m/s [E].

Practice

1. (a) Determine the instantaneous velocity at $t = 1.0$ s for the graph shown in Figure 6. [ans: 2.0 m/s [E]]
   (b) Determine the instantaneous velocity at $t = 3.0$ s for the graph shown in Figure 6. [ans: 6.0 m/s [E]]
   (c) Compare your answers to (a) and (b) with the solution to Sample Problem 1 above. Is it possible that the object is moving with constant acceleration? Explain. T/I
2. (a) Determine the instantaneous velocity at $t = 5.0$ s for the graph shown in **Figure 7**. [ans: 30 m/s [E]]
   (b) Determine the average velocity from $t = 0$ s to $t = 10.0$ s for the graph **Figure 7**. [ans: 30 m/s [E]]
   (c) Notice that for the motion described in Figure 7, $t = 5.0$ s is the midpoint in time. Write a statement describing the relationship that exists between the average velocity and the instantaneous velocity at the midpoint in time when an object is accelerating uniformly. T/I C

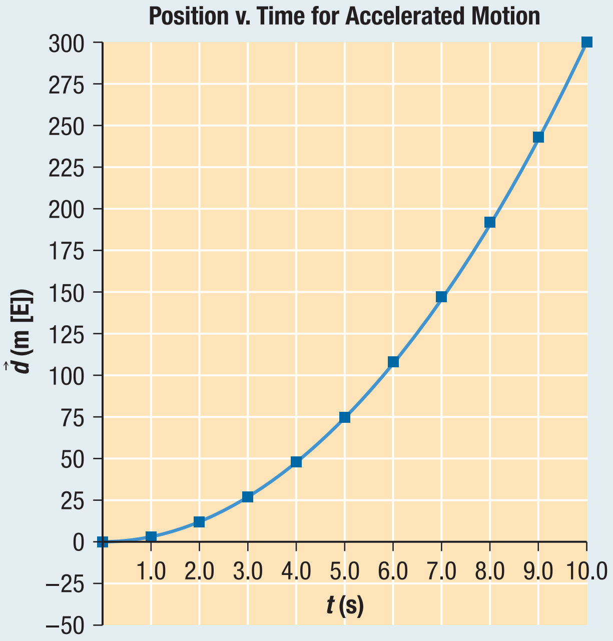


Figure 7

Note that in Tutorial 4, the average velocity over the first 2.0 s of the motion was less than the instantaneous velocity at 2.0 s. For motion with non-uniform velocity but uniform acceleration, average and instantaneous velocities are not necessarily equal. The only situation where the average velocity and the instantaneous velocity are the same is at the midpoint in the time interval.

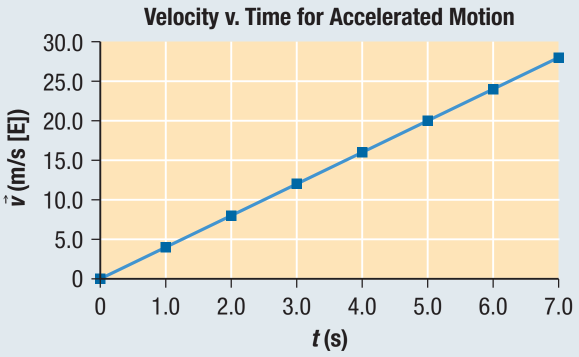
1.3 Summary

- Acceleration describes change in velocity over time.
- The slope of a velocity–time graph gives the acceleration of the object whose motion it describes.
- The area under a velocity–time graph gives the displacement of the object whose motion it describes.
- The instantaneous velocity of an object is its velocity at a specific instant in time. It is equal to the slope of the tangent to the position–time graph at that instant in time.
- For motion with non-uniform velocity, average and instantaneous velocities are not necessarily equal.

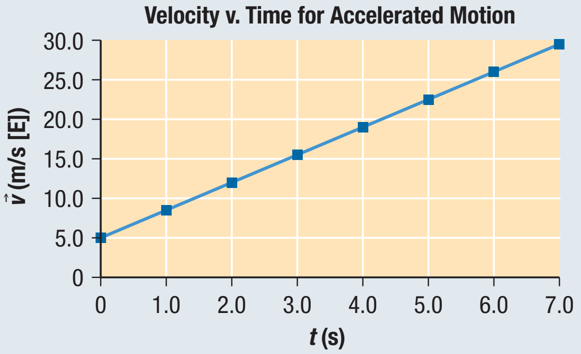
1.3 Questions

1. Describe three characteristics that an accelerating object may exhibit. Give a real-world example of each characteristic. K/U C
2. Describe, in your own words, how you would determine the acceleration of an object from a velocity–time graph. K/U C
3. Describe, in your own words, how you would determine the displacement of an object from a velocity–time graph. K/U C
4. Determine the average acceleration described by each of the following graphs. T/I

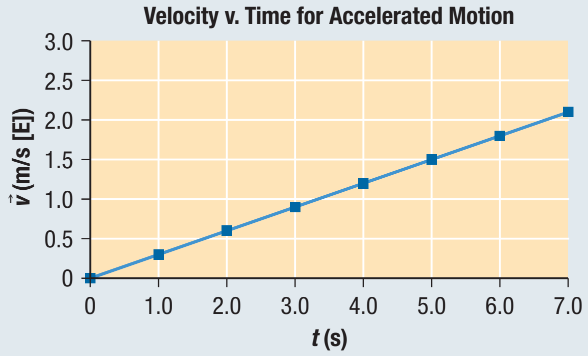
(a)



(b)



(c)



5. One of your classmates makes the following statement: "If an object has an initial velocity of 10 m/s [N] and a final velocity of 10 m/s [S], this object has clearly not accelerated, as it is travelling at a constant speed." Write an email to this student explaining why this statement is incorrect. K/U C
6. (a) Describe the motion of the object in all three segments of the graph shown in **Figure 8**.
   (b) Calculate the average acceleration of the object in all three segments of the graph in Figure 8.
   (c) Calculate the total displacement of the object from 0 s to 4.0 s, from 4.0 s to 7.0 s, and from 7.0 s to 10.0 s. T/I C

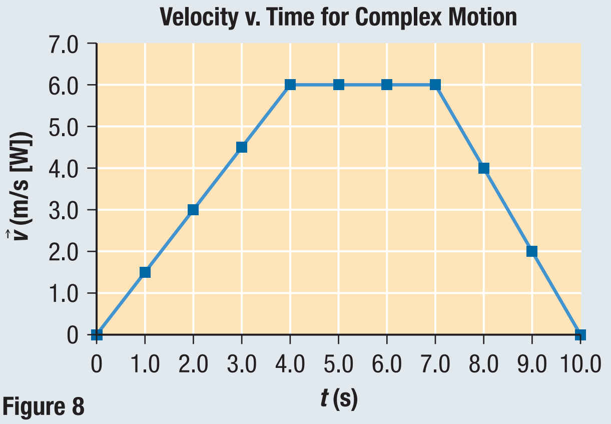


Figure 8

7. What is the average acceleration of a sports car that increases its velocity from 2.0 m/s [W] to 4.5 m/s [W] in 1.9 s? T/I
8. If a child on a bicycle can accelerate at an average rate of 0.53 m/s^2, how long would it take to increase the bicycle's velocity from 0.68 m/s [N] to 0.89 m/s [N]? T/I
9. (a) While approaching a red light, a student driver begins to apply the brakes. If the car's brakes can cause an average acceleration of 2.90 m/s^2 [S] and it takes 5.72 s for the car to come to rest, what was the car's initial velocity?
   (b) What is the significance of the direction of the initial velocity and that of the acceleration? T/I
10. What is the average acceleration of a tennis ball that has an initial velocity of 6.0 m/s [E] and a final velocity of 7.3 m/s [W], if it is in contact with a tennis racket for 0.094 s? T/I
11. (a) Determine the instantaneous velocity at $t = 6.0$ s in **Figure 9**.
    (b) Determine the average velocity of the motion depicted in Figure 9. T/I

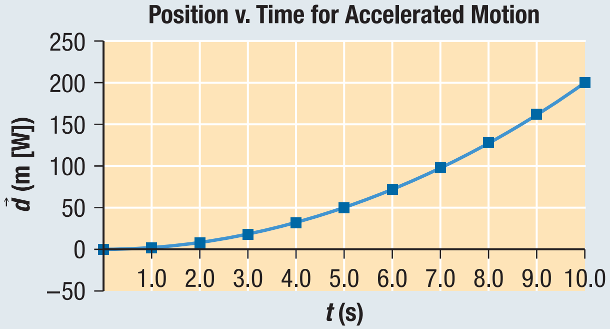


Figure 9

Comparing Graphs of Linear Motion

1.4

Cheetahs are adapted for speed—they are the fastest land animals. They can accelerate at faster rates than most sports cars (**Figure 1**). Cheetahs have been measured accelerating at rates greater than 10 m/s^2. To put this in perspective, a sports car can accelerate at approximately 7.2 m/s^2. In fact, cheetahs are capable of accelerating from rest to 10 m/s in only three strides.

You have already seen how position–time and velocity–time graphs can be used to analyze the linear motion of objects. In this section, we will introduce acceleration–time graphs and use all three types of graphs to analyze motion in more detail.

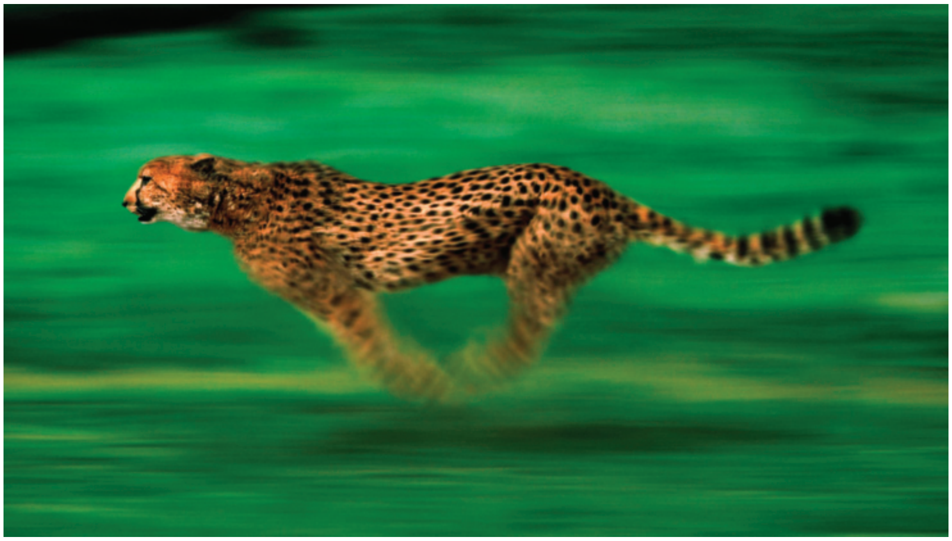


Figure 1 Cheetahs have the greatest acceleration of any animal.

Acceleration–Time Graphs

Earlier in this chapter, you learned how to find the displacement, or change in position, of an object by determining the area under a velocity–time graph. In a similar way, we can determine the change in velocity of an object from the area under an **acceleration–time graph**, which has acceleration on the vertical axis and time on the horizontal axis.

acceleration–time graph a graph describing motion of an object, with acceleration on the vertical axis and time on the horizontal axis

Consider the acceleration–time graph in **Figure 2**, which shows the motion of a cheetah. The points plotted on this graph lie along a horizontal straight line with a non-zero *y*-intercept. The acceleration is a constant 4.0 m/s^2, so this graph represents uniform acceleration.

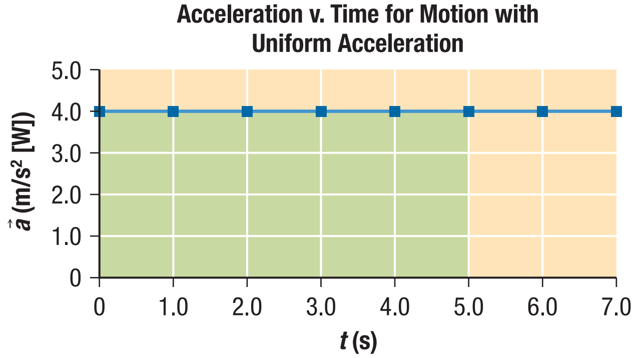


Figure 2 Acceleration–time graph showing motion with uniform acceleration

Investigation **1.4.1**

Uniform Velocity (p. 47)
In this investigation, you will use a motion sensor to generate different types of motion graphs for an object moving with uniform velocity, and analyze these graphs.

If we calculate the area under the acceleration–time graph in Figure 2 from 0 s to 5.0 s, we will be determining the change in velocity of the object from $t = 0$ s to $t = 5.0$ s:

$$A = lw$$

$$= (5.0\ \cancel{\text{s}})\left(4.0\ \frac{\text{m}}{\text{s}^{\cancel{2}}}\ [\text{W}]\right)$$

$$A = 20\ \text{m/s}\ [\text{W}]$$

Since the units are metres per second, the area we calculated represents a change in velocity.

The area under an acceleration–time graph represents the change in velocity of an object.

If the initial velocity of the cheetah is zero (the object is at rest), the final velocity is equal to the change in velocity, 20 m/s [W]. If the initial velocity is 5 m/s [W], however, then the graph tells us that the final velocity is

$$5\ \text{m/s}\ [\text{W}] + 20\ \text{m/s}\ [\text{W}] = 25\ \text{m/s}\ [\text{W}]$$

The graph does not tell us what the initial and final velocities are; it just tells us the change in velocity that occurs in the time interval.

Relationships among Linear Motion Graphs

Investigation **1.4.2**

Motion Down a Ramp (p. 48)
In this investigation, you will use a motion sensor and different types of motion graphs to analyze the motion of an object rolling down a ramp.

Graphical analysis is one of the most powerful analytical tools available to physicists. In studying the motion of objects, analyzing position–time, velocity–time, and acceleration–time graphs can help us gain insight into real-life events such as the motion of the cheetah shown in Figure 1. This is particularly important because most objects in nature do not come equipped with a speedometer.

Figure 3 compares the three types of graphs of linear motion. All three graphs represent the same type of motion: uniform acceleration. Nevertheless, the three graphs look very different. When analyzing a motion graph, you may read information directly from the graph or determine further information by calculating the slope or the area of the graph.

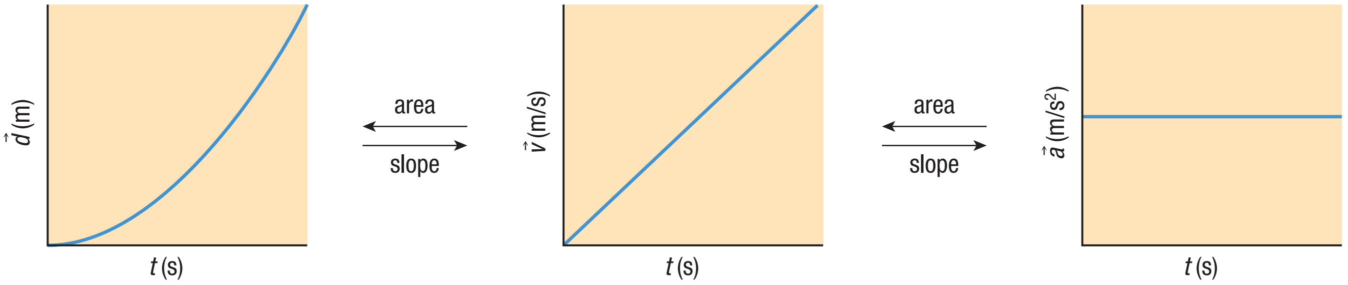


Figure 3 Position–time, velocity–time, and acceleration–time graphs of the same motion

Tutorial 1 Creating One Type of Motion Graph from Another

By using the information in **Figure 4**, we can analyze an acceleration–time graph further and get more information about the motion it describes.

Sample Problem 1: Creating a Velocity–Time Graph from an Acceleration–Time Graph

Use the acceleration–time graph in **Figure 4** to generate velocity and time data for the object. Then use these data to plot a velocity–time graph.

Step 1. To generate the velocity–time data, first calculate the area under the graph for several time points in Figure 4. Since the line is horizontal, we use the formula for the area of a rectangle, $A = lw$.

For Figure 4, $l = t$ (s); $w = \vec{a}$ (m/s^2 [W]); and $A = \vec{v}$ (m/s [W]), so in calculating $A = lw$, we are actually calculating $\vec{v} = (\Delta\vec{a})(\Delta t)$

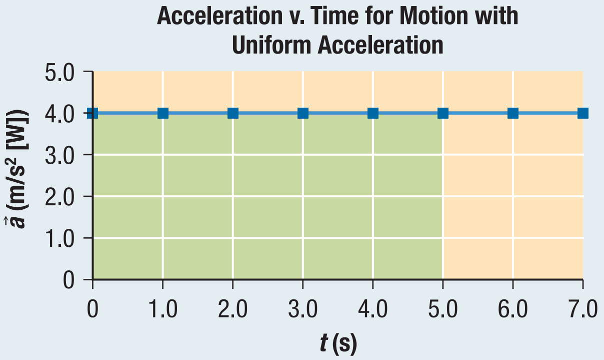


Figure 4 Using an acceleration–time graph to create other motion graphs

Step 2. **Table 1** shows the calculations for the area under the graph at 1 s intervals from $t = 0$ s to $t = 5.0$ s.

Table 1 Calculating the Velocity at Various Time Points in Figure 4

Time t (s)	Acceleration $\vec{a}$ (m/s^2 [W])	Equation $\vec{v} = (\Delta\vec{a})(\Delta t)$	Velocity $\vec{v}$ (m/s) [W]
0	4.0	$\vec{v} = \left(4.0\,\frac{\text{m}}{\text{s}^{\cancel{2}}}\,[\text{W}]\right)(0\,\cancel{\text{s}})$	0
1.0	4.0	$\vec{v} = \left(4.0\,\frac{\text{m}}{\text{s}^{\cancel{2}}}\,[\text{W}]\right)(1.0\,\cancel{\text{s}})$	4.0
2.0	4.0	$\vec{v} = \left(4.0\,\frac{\text{m}}{\text{s}^{\cancel{2}}}\,[\text{W}]\right)(2.0\,\cancel{\text{s}})$	8.0
3.0	4.0	$\vec{v} = \left(4.0\,\frac{\text{m}}{\text{s}^{\cancel{2}}}\,[\text{W}]\right)(3.0\,\cancel{\text{s}})$	12
4.0	4.0	$\vec{v} = \left(4.0\,\frac{\text{m}}{\text{s}^{\cancel{2}}}\,[\text{W}]\right)(4.0\,\cancel{\text{s}})$	16
5.0	4.0	$\vec{v} = \left(4.0\,\frac{\text{m}}{\text{s}^{\cancel{2}}}\,[\text{W}]\right)(5.0\,\cancel{\text{s}})$	20.0

Step 3. Plot the data to create a velocity–time graph (**Figure 5**).

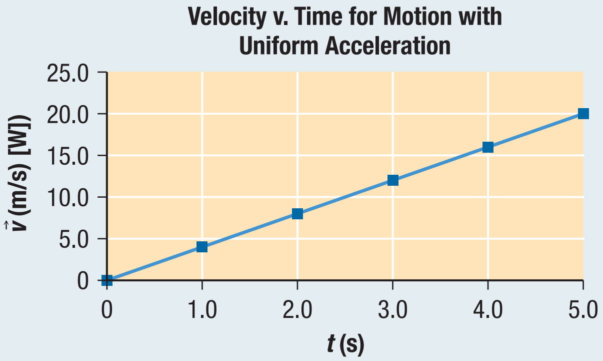


Figure 5 Velocity–time solution graph

Figure 5 shows the resulting graph. It is an increasing straight line with a zero intercept. It describes precisely the same motion that was described by the acceleration–time graph in Figure 4. Both graphs describe uniform acceleration.

Sample Problem 2: Creating an Acceleration–Time Graph from a Velocity–Time Graph

Use the velocity–time graph shown in **Figure 6** to plot the corresponding acceleration–time graph.

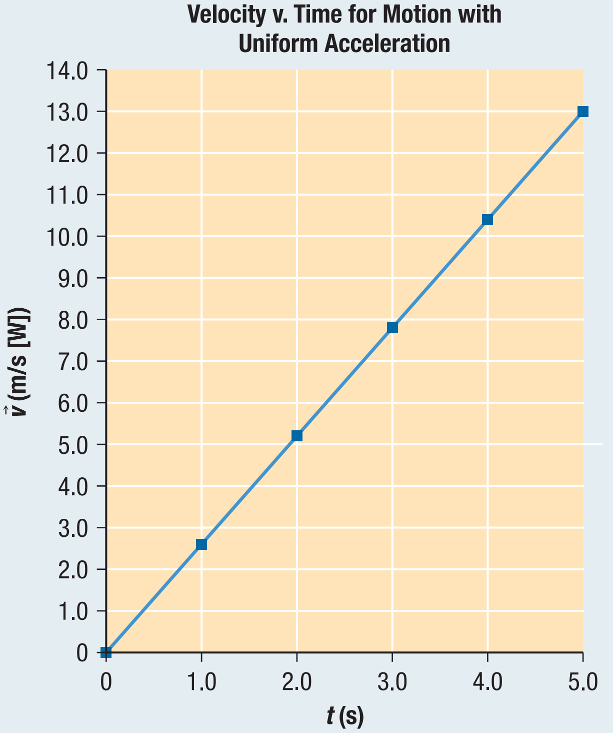


Figure 6 Given velocity–time graph

Step 1. The data plotted on the velocity–time graph in Figure 6 form an increasing straight-line graph with a zero intercept. You can determine acceleration from a velocity–time graph by calculating its slope. Since the velocity–time graph in Figure 6 is a straight line, its slope does not change. So we can calculate the slope or acceleration over any time interval.

$$\text{slope} = \frac{\text{rise}}{\text{run}}$$

$$\vec{a}_{\text{av}} = \frac{\Delta\vec{v}}{\Delta t}$$

$$= \frac{7.8\ \text{m/s}\ [\text{W}]}{3.0\ \text{s}}$$

$$\vec{a}_{\text{av}} = 2.6\ \text{m/s}^2\ [\text{W}]$$

Step 2. Use this value to create an acceleration–time graph (**Figure 7**).

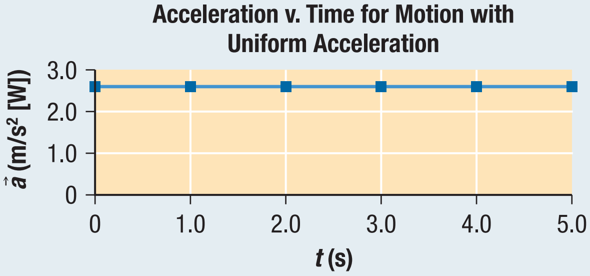


Figure 7 Acceleration–time solution graph

Figure 7 shows the corresponding acceleration–time graph. This graph shows a horizontal straight line with a *y*-intercept of 2.6 m/s^2 [W].

Note: If a velocity–time graph is not a straight line, you will need to determine the slope of the tangent for each time data point, and then use these data to plot the corresponding acceleration–time graph.

Practice

1. Generate position–time and acceleration–time data representing the motion of the object shown in **Figure 8**. Use the data to plot the corresponding position–time and acceleration–time graphs. T/I C

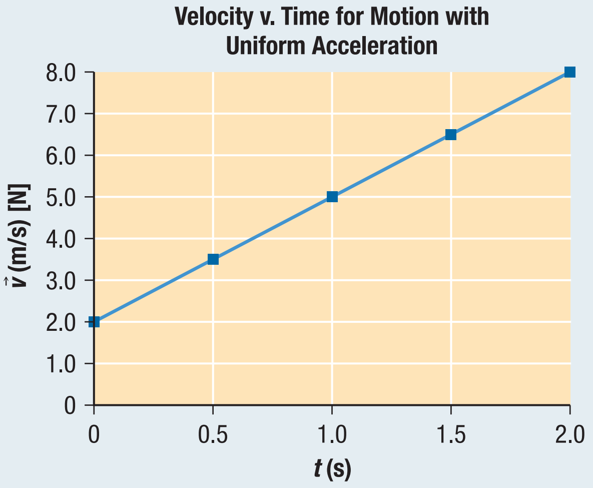


Figure 8

1.4 Summary

- The area under an acceleration–time graph gives the velocity of the object.
- Given one type of motion graph, you can read or calculate data from it in order to construct a different type of graph.

1.4 Questions

1. Copy and complete **Table 2** in your notebook by adding a check mark in each column that applies. K/U

Table 2

How do you determine …	Given a …	Read information from graph	Take the slope	Find the area
position	position–time graph			
velocity	position–time graph			
velocity	velocity–time graph			
velocity	acceleration–time graph			
acceleration	velocity–time graph			
acceleration	acceleration–time graph			

2. From the velocity–time graph in **Figure 9**, generate position–time data and then plot the corresponding position–time graph, assuming the initial position is 0 m. T/I C

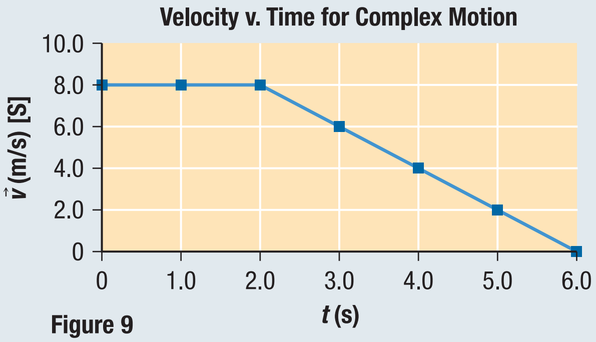


Figure 9

3. Consider the position–time graph shown in **Figure 10**. T/I
   (a) What is the position of the object at $t = 5.0$ s?
   (b) What is the instantaneous velocity of the object at $t = 3.0$ s?
   (c) What is the average velocity for the object's motion from 0 s to 6.0 s?

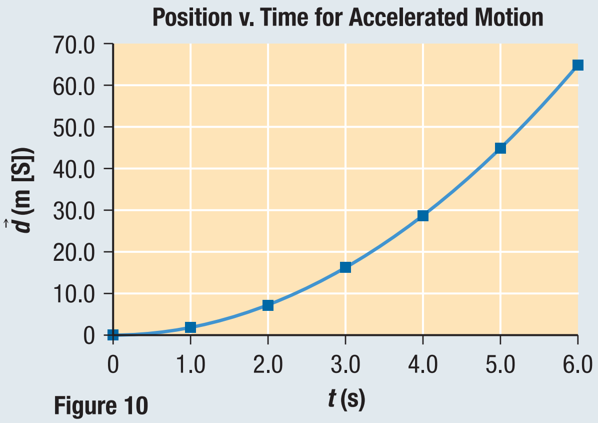


Figure 10

4. Use the data in the velocity–time graph shown in **Figure 11** to plot the corresponding acceleration–time graph. T/I C

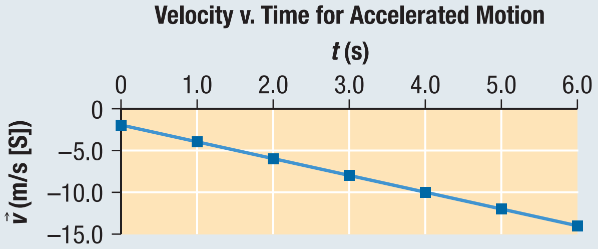


Figure 11

1.5

Five Key Equations for Motion with Uniform Acceleration

Graphical analysis is an important tool for physicists to use to solve problems. Sometimes, however, we have enough information to allow us to solve problems algebraically. Algebraic methods tend to be quicker and more convenient than graphical analysis. For example, if you want to determine how far a passing vehicle would travel in a given amount of time, you could perform an experiment using a motion sensor. You would collect position–time data with the motion sensor and then plot the data on a graph. From the graph, you could then measure how far the vehicle has gone in a given amount of time. However, if you were in the vehicle, you would simply use the vehicle's speedometer to determine the speed of the vehicle. Knowing the speed of your vehicle, you could easily determine how far it would travel in a given time interval using the equation $v_{av} = \frac{\Delta d}{\Delta t}$. As you can see, the best way to solve a problem is usually determined by the information that is available to you.

To be able to solve problems related to motion with uniform acceleration, in which the velocity may change but the acceleration is constant, we need to derive algebraic equations that describe this type of motion. We will start with equations that we have already used in previous sections.

A Displacement Equation for Uniformly Accelerated Motion

The velocity–time graph in **Figure 1** shows a straight line with a non-zero intercept. This graph is a non-horizontal straight line, showing that the object is undergoing uniform, or constant, acceleration. In other words, the velocity is increasing at a uniform, or constant, rate. We know that to determine the displacement of this object from the velocity–time graph, we must determine the area under the line. For the graph in Figure 1, we must determine the area of a rectangle and a triangle:

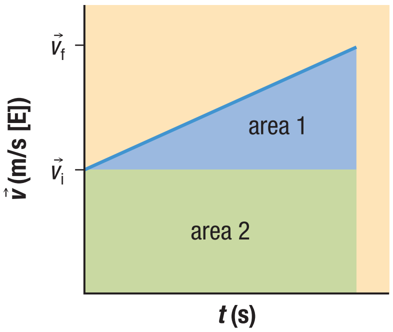


Figure 1 A velocity–time graph for an object undergoing uniform acceleration

$$\begin{aligned}\Delta\vec{d} &= A_{\text{triangle}} + A_{\text{rectangle}}\\ &= \frac{1}{2}bh + lw\\ &= \frac{1}{2}\Delta t(\vec{v}_f - \vec{v}_i) + \Delta t\vec{v}_i\\ &= \frac{1}{2}\vec{v}_f\Delta t - \frac{1}{2}\vec{v}_i\Delta t + \vec{v}_i\Delta t\\ &= \frac{1}{2}\vec{v}_f\Delta t + \frac{1}{2}\vec{v}_i\Delta t\end{aligned}$$

$$\Delta\vec{d} = \left(\frac{\vec{v}_f + \vec{v}_i}{2}\right)\Delta t \text{ (Equation 1)}$$

LEARNING **TIP**

Interpreting Areas Under a Motion Graph

Notice that the rectangular area (green) in Figure 1 represents the displacement the object would have undergone had it continued at constant velocity $\vec{v}_i$. The triangular area (blue) represents the extra displacement the object experienced due to its acceleration.

We can use Equation 1 to determine the displacement of an object that is undergoing uniform acceleration. Equation 1 is very similar to an equation that we previously developed from the defining equation for average velocity: $\Delta\vec{d} = \vec{v}_{av}\Delta t$. We can relate the average velocity to the initial and final velocities by the equation

$$\vec{v}_{av} = \left(\frac{\vec{v}_f + \vec{v}_i}{2}\right)$$

Then substituting $\vec{v}_{av}$ in place of $\left(\frac{\vec{v}_f + \vec{v}_i}{2}\right)$ in Equation 1 gives $\Delta\vec{d} = \vec{v}_{av}\Delta t$ directly.

As you will see, Equation 1 can help us to solve many motion problems. However, in some situations we will not know the initial velocity, the final velocity, or the time interval for a given scenario. We could use the defining equation for acceleration in a two-step process, but this tends to be difficult. To simplify things, we can derive a number of other motion equations that will allow us to solve problems in one step.

Additional Motion Equations

Consider the defining equation for acceleration: $\vec{a}_{av} = \dfrac{\vec{v}_f - \vec{v}_1}{\Delta t}$

If we rearrange this equation to solve for final velocity ($\vec{v}_f$), we get Equation 2:

$$\vec{v}_f = \vec{v}_i + \vec{a}_{av}\Delta t \text{ (Equation 2)}$$

You may use Equation 2 in problems that do not directly involve displacement.

If we substitute the expression $v_i + \vec{a}_{av}\Delta t$ from Equation 2 into Equation 1, we get

$$\vec{v}_f = \vec{v}_i + \vec{a}_{av}\Delta t \text{ (Equation 2)}$$

$$\begin{aligned}\Delta\vec{d} &= \left(\frac{\vec{v}_f + \vec{v}_i}{2}\right)\Delta t \text{ (Equation 1)}\\ &= \frac{1}{2}(\vec{v}_i + \vec{a}_{av}\Delta t + \vec{v}_i)\Delta t\\ &= \frac{1}{2}(2\vec{v}_i + \vec{a}_{av}\Delta t)\Delta t\end{aligned}$$

$$\Delta\vec{d} = \vec{v}_i\Delta t + \frac{1}{2}\vec{a}_{av}\Delta t^2 \text{ (Equation 3)}$$

This is Equation 3, which allows you to determine the displacement of an object moving with uniform acceleration given a value for acceleration rather than a final velocity.

The Five Key Equations of Accelerated Motion

Table 1 shows the five key equations of accelerated motion. You should be able to solve any kinematics question by correctly choosing one of these five equations. You have seen how the first three are developed. We will leave the others to be developed as an exercise.

Table 1 The Five Key Equations of Accelerated Motion

	Equation	Variables found in equation	Variables not in equation
Equation 1	$\Delta\vec{d} = \left(\frac{\vec{v}_f + \vec{v}_i}{2}\right)\Delta t$	$\Delta\vec{d}, \Delta t, \vec{v}_f, \vec{v}_i$	$\vec{a}_{av}$
Equation 2	$\vec{v}_f = \vec{v}_i + \vec{a}_{av}\Delta t$	$\vec{a}_{av}, \Delta t, \vec{v}_f, \vec{v}_i$	$\Delta\vec{d}$
Equation 3	$\Delta\vec{d} = \vec{v}_i\Delta t + \frac{1}{2}\vec{a}_{av}\Delta t^2$	$\Delta\vec{d}, \vec{a}_{av}, \Delta t, \vec{v}_i$	$\vec{v}_f$
Equation 4	$v_f^2 = v_i^2 + 2a_{av}\Delta d$	$\Delta d, a_{av}, v_f, v_i$	Δt
Equation 5	$\Delta\vec{d} = \vec{v}_f\Delta t - \frac{1}{2}\vec{a}_{av}\Delta t^2$	$\Delta\vec{d}, \vec{a}_{av}, \Delta t, \vec{v}_f$	$\vec{v}_i$

Tutorial 1 Using the Five Key Equations of Accelerated Motion

The following Sample Problems will demonstrate how to choose equations and solve problems involving the five key motion equations.

Sample Problem 1

A sports car approaches a highway on-ramp at a velocity of 20.0 m/s [E]. If the car accelerates at a rate of 3.2 m/s^2 [E] for 5.0 s, what is the displacement of the car?

Given: $\vec{v}_\text{i} = 20.0\text{ m/s }[\text{E}]$; $\vec{a}_\text{av} = 3.2\text{ m/s}^2[\text{E}]$; $\Delta t = 5.0\text{ s}$

Required: $\Delta\vec{d}$

Analysis: Our first task is to determine which of the five equations of accelerated motion to use. Usually, you can solve a problem using only one of the five equations. We simply identify which equation contains all the variables for which we have given values and the unknown variable that we are asked to calculate. In Table 1, we see that Equation 3 has all the given variables and will allow us to solve for the unknown variable.

$$\Delta\vec{d} = \vec{v}_\text{i}\Delta t + \frac{1}{2}\vec{a}_\text{av}\Delta t^2$$

Solution:
$$\begin{aligned}\Delta\vec{d} &= \vec{v}_\text{i}\Delta t + \frac{1}{2}\vec{a}_\text{av}\Delta t^2 \\ &= \left(20.0\,\frac{\text{m}}{\cancel{\text{s}}}\,[\text{E}]\right)(5.0\,\cancel{\text{s}}) + \frac{1}{2}\left(3.2\,\frac{\text{m}}{\cancel{\text{s}^2}}\,[\text{E}]\right)(5.0\,\cancel{\text{s}})^2 \\ &= 100\text{ m }[\text{E}] + 40\text{ m }[\text{E}] \\ \Delta\vec{d} &= 1.4 \times 10^2\text{ m }[\text{E}]\end{aligned}$$

Statement: During the 5.0 s time interval, the car is displaced 1.4 × 10^2 m [E].

Sample Problem 2

A sailboat accelerates uniformly from 6.0 m/s [N] to 8.0 m/s [N] at a rate of 0.50 m/s^2 [N]. What distance does the boat travel?

Given: $v_\text{i} = 6.0\text{ m/s}$; $v_\text{f} = 8.0\text{ m/s}$; $a_\text{av} = 0.50\text{ m/s}^2$

Required: Δd

Analysis: In Table 1, we see that Equation 4 will allow us to solve for the unknown variable. First, we rearrange the equation to solve for Δd:

$$\begin{aligned}v_\text{f}^2 &= v_\text{i}^2 + 2a_\text{av}\Delta d \\ v_\text{f}^2 - v_\text{i}^2 &= 2a_\text{av}\Delta d \\ \Delta d &= \frac{v_\text{f}^2 - v_\text{i}^2}{2a_\text{av}}\end{aligned}$$

Solution:
$$\begin{aligned}\Delta d &= \frac{v_\text{f}^2 - v_\text{i}^2}{2a_\text{av}} \\ &= \frac{\left(8.0\,\frac{\text{m}}{\text{s}}\right)^2 - \left(6.0\,\frac{\text{m}}{\text{s}}\right)^2}{2\left(0.50\,\frac{\text{m}}{\text{s}^2}\right)} \\ &= \frac{(64 - 36)\frac{\text{m}^2}{\cancel{\text{s}^2}}}{1\,\frac{\cancel{\text{m}}}{\cancel{\text{s}^2}}} \\ \Delta d &= 28\text{ m}\end{aligned}$$

Statement: The boat travels a distance of 28 m.

Sample Problem 3

A dart is thrown at a target that is supported by a wooden backstop. It strikes the backstop with an initial velocity of 350 m/s [E]. The dart comes to rest in 0.0050 s.

(a) What is the acceleration of the dart?

(b) How far does the dart penetrate into the backstop?

For (a):

Given: $\vec{v}_\text{i} = 350\text{ m/s }[\text{E}]$; $\vec{v}_\text{f} = 0\text{ m/s}$; $\Delta t = 0.0050\text{ s}$

Required: $\vec{a}_\text{av}$

Analysis: We may use the defining equation for acceleration.

$$\vec{a}_\text{av} = \frac{\vec{v}_\text{f} - \vec{v}_\text{i}}{\Delta t}$$

Solution:
$$\begin{aligned}\vec{a}_\text{av} &= \frac{\vec{v}_\text{f} - \vec{v}_\text{i}}{\Delta t} \\ &= \frac{0\,\frac{\text{m}}{\text{s}} - 350\,\frac{\text{m}}{\text{s}}\,[\text{E}]}{0.0050\text{ s}} \\ &= -70\,000\text{ m/s}^2\,[\text{E}] \\ \vec{a}_\text{av} &= 7.0 \times 10^4\text{ m/s}^2\,[\text{W}]\end{aligned}$$

Notice that the acceleration is in the opposite direction to the initial motion. This must be true in order for the velocity of the dart to decrease to zero as it comes to rest. If the acceleration were in the same direction as the initial velocity, the final velocity would be greater than the initial velocity.

Statement: The acceleration of the dart is 7.0 × 10^4 m/s^2 [W].

To solve (b), we have sufficient information to solve the problem using any equation with displacement in it. Generally speaking, in a two-part problem like this, it is a good idea to try to find an equation that uses only given information. Then, if we have made an error in calculating the first part (acceleration), our next calculation would be unaffected by the error. Therefore, we will use Equation 1 to solve (b), since it can be solved using only given information.

Given: $\vec{v}_i = 350\text{ m/s [E]}$; $\vec{v}_f = 0\text{ m/s}$; $\Delta t = 0.0050\text{ s}$

Required: $\Delta\vec{d}$

Analysis: $\Delta\vec{d} = \left(\dfrac{\vec{v}_f + \vec{v}_i}{2}\right)\Delta t$

Solution: $\Delta\vec{d} = \left(\dfrac{\vec{v}_f + \vec{v}_i}{2}\right)\Delta t$

$$= \left(\frac{0\,\frac{\text{m}}{\cancel{\text{s}}} + 350\,\frac{\text{m}}{\cancel{\text{s}}}\,[\text{E}]}{2}\right)(0.0050\,\cancel{\text{s}})$$

$$\Delta\vec{d} = 0.88\text{ m [E]}$$

Statement: The displacement of the dart into the backstop is 0.88 m [E].

Practice

1. A football player initially at rest accelerates uniformly as she runs down the field, travelling 17 m [E] in 3.8 s. What is her final velocity? T/I [ans: 8.9 m/s [E]]
2. A child on a toboggan sits at rest on the top of a tobogganing hill. If the child travels 70.0 m [downhill] in 5.3 s while accelerating uniformly, what acceleration does the child experience? T/I [ans: 5.0 m/s^2 [downhill]]

1.5 Summary

- The five key equations of accelerated motion, listed in Table 1 on page 37, apply to motion with uniform (constant) acceleration. They involve the variables for displacement, initial velocity, final velocity, acceleration, and time interval.
- When solving uniform acceleration problems, choose which equation(s) to use based on the given and required variables of the problem.

1.5 Questions

1. A car accelerates from rest at a rate of 2.0 m/s^2 [N]. What is the displacement of the car at $t = 15$ s? T/I
2. An astronaut is piloting her spacecraft toward the International Space Station. To stop the spacecraft, she fires the retro-rockets, which cause the spacecraft to slow down from 20.0 m/s [E] to 0.0 m/s in 12 s. T/I
   (a) What is the acceleration of the spacecraft?
   (b) What is the displacement of the spacecraft when it comes to rest?
3. A helicopter travelling at a velocity of 15 m/s [W] accelerates uniformly at a rate of 7.0 m/s^2 [E] for 4.0 s. What is the helicopter's final velocity? T/I
4. Two go-carts, A and B, race each other around a 1.0 km track. Go-cart A travels at a constant speed of 20.0 m/s. Go-cart B accelerates uniformly from rest at a rate of 0.333 m/s^2. Which go-cart wins the race and by how much time? T/I
5. A boat increases its speed from 5.0 m/s to 7.5 m/s over a distance of 50.0 m. What is the boat's acceleration? T/I
6. Within 4.0 s of liftoff, a spacecraft that is uniformly accelerating straight upward from rest reaches an altitude of 4.50×10^2 m [up]. T/I
   (a) What is the spacecraft's acceleration?
   (b) At what velocity is the spacecraft travelling when it reaches this altitude?
7. Derive Equation 4 and Equation 5 in Table 1 on page 37 by substituting other expressions. T/I

1.6 Acceleration Near Earth's Surface

During a basketball game, the player takes the ball and shoots it toward the basket (**Figure 1**). The ball briefly skims the rim, then drops through the net to the floor. The player makes the basket because of her skill, with a little bit of help from the force of gravity. Gravity causes all objects to accelerate toward Earth's centre. If you have accidentally dropped an object such as a glass, you have directly experienced how significant the effect of gravity is.

LEARNING **TIP**

Describing Vertical Motion Directions
Vertical motion problems are vector questions that require directions to be indicated. Directions can be simplified by defining "up" as positive and "down" as negative. This means that the acceleration due to gravity should be negative in your calculations.

Figure 1 Earth's gravity plays a key role in basketball and most other sports.

Acceleration Due to Gravity

acceleration due to gravity (*g*) the acceleration that occurs when an object is allowed to fall freely; close to Earth's surface, *g* has a value of 9.8 m/s^2

Acceleration due to gravity is the acceleration that occurs when an object is allowed to fall freely. The symbol for acceleration due to gravity is *g*. Physicists have determined that the average value of *g* measured very close to Earth's surface is 9.8 m/s^2. Different places on Earth have different values for *g*. For example, the value of *g* in Mexico City is slightly but measurably lower than the average of 9.8 m/s^2 because the city has a very high elevation and is therefore farther from Earth's centre. This had an interesting effect on the 1968 Summer Olympic Games, which were held in Mexico City. Many high jump, long jump, and pole-vaulting records were broken during these Olympic Games, attributed in part to the lower value of *g*. The value of *g* is different on different planets and other celestial objects.

free fall the acceleration due to gravity of an object in the absence of air resistance

The acceleration due to gravity of an object near Earth's surface will be about 9.8 m/s^2 only if it is dropped in a vacuum. This type of motion is referred to as **free fall**, which is acceleration that occurs when there is no air resistance or other force affecting the motion of the object besides gravity.

Uniform Vertical Acceleration

All objects that move freely in the vertical direction experience acceleration due to gravity (*g*). In the previous section, you worked with the five key motion equations. Since we know the average value of *g* close to Earth's surface, we can use the motion equations to explore how gravity affects objects that are moving vertically.

Tutorial 1 Motion of an Object Falling Straight Down

The following Sample Problems will demonstrate, using the five key equations of motion, how to solve problems involving vertical motion. You might want to review the equations in Table 1 on page 37.

Sample Problem 1: Determining the Time It Takes for an Object to Fall to the Ground

A flowerpot is knocked off a window ledge and accelerates uniformly to the ground. If the window ledge is 10.0 m above the ground and there is no air resistance, how long does it take the flowerpot to reach the ground?

Solution

We know that the motion of the flowerpot is straight down. However, we cannot describe the direction of the vector as we have previously, using [E], [W], [N], or [S]. So we will let vectors with directions up and to the right be indicated by positive values. Vectors with directions down and to the left will be indicated by negative values.

Since the flowerpot is not thrown upward or downward, we can assume that it was initially at rest. Therefore, the initial velocity is 0 m/s.

Given: $\Delta\vec{d} = -10.0\text{ m}$; $\vec{a} = \vec{g} = -9.8\text{ m/s}^2$; $\vec{v}_i = 0\text{ m/s}$

Required: Δt

Analysis: Since we are given the displacement, acceleration, and initial velocity of the flowerpot, we can use Equation 3 to solve for time.

$$\Delta\vec{d} = \vec{v}_i\Delta t + \frac{1}{2}\vec{a}(\Delta t)^2$$

Solution: Notice that the given displacement and acceleration values are both negative, because both vectors point downward.

In general, it is not valid to divide one vector by another. However, since the motion is in a straight line, and the directions are given by the minus signs, we are able to divide the vector values. This equation can be rewritten as follows.

$$\Delta\vec{d} = \frac{1}{2}\vec{a}(\Delta t)^2$$

$$\Delta t = \sqrt{\frac{2\Delta d}{a}}$$

$$\Delta t = \sqrt{\frac{2(-10.0\ \cancel{\text{m}})}{-9.8\ \cancel{\text{m}}/\text{s}^2}}$$

$$\Delta t = 1.4\text{ s}$$

We know we should take the positive root because time intervals are always positive.

Statement: The flowerpot will take 1.4 s to reach the ground.

Sample Problem 2: Determining the Final Velocity for a Falling Object

What is the final velocity of the flowerpot in Sample Problem 1 just before it hits the ground?

Solution

To solve this problem, we need to find the final velocity of the flowerpot just before it hits the ground. If the question asked for its velocity after it had hit the ground and came to rest, then the final velocity would be 0 m/s. Here, we are determining the velocity while the flowerpot is still in motion, just before it hits the ground.

We will again write vectors with directions that are up and to the right as having positive values and those with directions down and to the left as having negative values.

Given: $\Delta\vec{d} = -10.0\text{ m}$; $\vec{a} = \vec{g} = -9.8\text{ m/s}^2$; $\vec{v}_i = 0\text{ m/s}$

Required: $\vec{v}_f$

Analysis: We can choose any of the five key equations of motion that has $\vec{v}_f$ as a variable. It is always wise to choose the equation that only requires you to use given information. We will use the vector directions for the given variables but will only calculate the magnitude of the final velocity. We know that the direction of the final velocity must be downward.

$$v_f^2 = v_i^2 + 2a\Delta d$$

$$v_f = \sqrt{v_i^2 + 2a\Delta d}$$

Solution: Since the initial velocity is zero,

$$\begin{aligned} v_f &= \sqrt{2a\Delta d} \\ &= \sqrt{2\left(-9.8\ \frac{\text{m}}{\text{s}^2}\right)(-10.0\text{ m})} \\ &= 14\text{ m/s} \end{aligned}$$

Statement: The flowerpot is travelling at 14 m/s downward just before it hits the ground.

Practice

1. A ball is dropped from the roof of a building. If it takes the ball 2.6 s to reach the ground, how tall is the building? T/I [ans: 33 m]
2. A hot air balloon is hovering at a height of 52 m above the ground. A penny is dropped from the balloon. Assume no air resistance. T/I
   (a) How long does it take the penny to hit the ground? [ans: 3.3 s]
   (b) What is the final velocity of the penny just before it hits the ground? [ans: 32 m/s]

Tutorial 2 Motion of an Object Thrown Straight Up

The following Sample Problems involve analyzing the motion of an object that is first thrown straight up and then falls to Earth.

Sample Problem 1: Determining the Height Reached by a Ball Thrown Straight Up in the Air

A tennis ball is thrown straight up in the air, leaving the person's hand with an initial velocity of 3.0 m/s, as shown in **Figure 2** on the next page. How high, from where it was thrown, does the ball go?

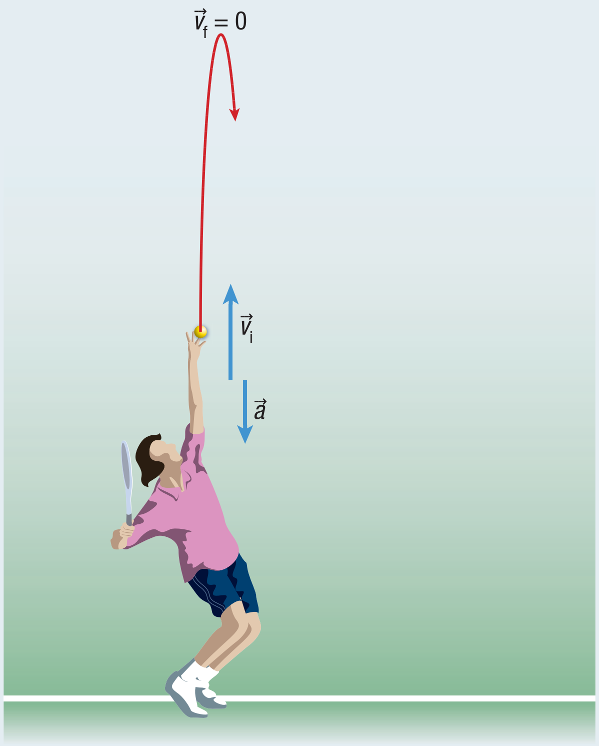


Figure 2 The motion of a ball thrown straight upward

Figure 2 shows the path of the tennis ball. Notice that the vectors for the initial velocity, $\vec{v}_i$, and the acceleration, $\vec{a}$, are in opposite directions to each other. Using our previous convention, the upward vector will be made positive and the downward vector negative. At its maximum height, the ball comes to rest momentarily, so the final velocity, $\vec{v}_f$, is zero. Then we can use Equation 4.

Given: $\vec{v}_i = 3.0$ m/s; $\vec{a} = -9.8$ m/s^2; $\vec{v}_f = 0$ m/s

Required: Δd

Analysis: $v_f^2 = v_i^2 + 2a\Delta d$

$$0 = v_i^2 + 2a\Delta d$$

$$-v_i^2 = 2a\Delta d$$

$$\Delta d = \frac{-v_i^2}{2a}$$

Solution: $\Delta d = \dfrac{-v_i^2}{2a}$

$$= \frac{-\left(3.0\,\dfrac{\text{m}}{\text{s}}\right)^2}{2\left(-9.8\,\dfrac{\text{m}}{\text{s}^2}\right)}$$

$$= \frac{-9.0\,\dfrac{\text{m}^{\cancel{2}}}{\cancel{\text{s}^2}}}{-19.6\,\dfrac{\cancel{\text{m}}}{\cancel{\text{s}^2}}}$$

$$\Delta d = 0.46 \text{ m}$$

Statement: The maximum height attained by the tennis ball is 0.46 m (46 cm).

Sample Problem 2: Determining the Time for a Ball Thrown Upward to Attain Its Maximum Height

How long will it take the ball shown in Figure 2 to reach its maximum height?

Given: $\vec{v}_i = 3.0$ m/s; $\vec{a} = -9.8$ m/s^2; $\vec{v}_f = 0$ m/s

Required: Δt

Analysis: To determine the time that this motion takes, we will identify an equation that uses only given information.

$$\vec{a} = \frac{\vec{v}_f - \vec{v}_i}{\Delta t}$$

$$\Delta t = \frac{\vec{v}_f - \vec{v}_i}{\vec{a}}$$

Since the final velocity is equal to zero,

$$\Delta t = \frac{-\vec{v}_i}{\vec{a}}$$

Solution: $\Delta t = \dfrac{-\vec{v}_i}{\vec{a}}$

$$= \frac{-\left(3.0\,\dfrac{\cancel{\text{m}}}{\text{s}}\right)}{-9.8\,\dfrac{\cancel{\text{m}}}{\text{s}^{\cancel{2}}}}$$

$$\Delta t = 0.31 \text{ s}$$

Statement: It will take the tennis ball 0.31 s to reach its maximum height.

Practice

1. A golf ball is thrown straight up in the air at a velocity of 8.3 m/s. T/I
   (a) Determine the maximum height of the golf ball. [ans: 3.5 m]
   (b) How long will it take the ball to reach its maximum height? [ans: 0.85 s]
   (c) How long will it take the ball to fall from its maximum height to the height from which it was initially launched? [ans: 0.85 s]
2. A rock is thrown downward from a bridge that is 12 m above a small creek. The rock has an initial velocity of 3.0 m/s downward. What is the velocity of the rock just before it hits the water? T/I [ans: 16 m/s down]

Figure 3 The value of 9.8 m/s^2 for acceleration near Earth assumes that there are no other forces acting on an object, such as air resistance.

Free Fall and Terminal Velocity

In real-life situations, there will always be some air resistance. Sometimes air resistance can be enough to have a significant effect on the motion of a falling object. For example, when a parachutist jumps out of an aircraft, he can control the amount of air resistance based on how he positions his body. If the parachutist dives out of the aircraft head first, he will experience very little air resistance. Most parachutists will try to fall so that as much of the surface area of their body is in contact with the air as possible. In other words, most parachutists will fall in a belly flop (**Figure 3**).

When the air resistance on the parachutist is equal to the force due to gravity acting on the parachutist, the parachutist will stop accelerating and stay at a constant velocity, called the **terminal velocity**. You will learn more about air resistance and free fall in Unit 2.

terminal velocity the velocity of an object when the force due to air resistance equals the force due to gravity on the object

1.6 Summary

- The symbol g is used to represent the acceleration due to gravity.
- All objects in free fall close to Earth's surface will accelerate at 9.8 m/s^2 toward Earth's centre.
- Air resistance can cause objects to accelerate at values less than g.
- When an object reaches terminal velocity, it will fall at a constant velocity.

1.6 Questions

1. Describe the motion of an object that is dropped close to Earth's surface. K/U C
2. A basketball player jumps up to make a basket and appears to "hang" in mid-air. Write a brief description explaining to a Grade 9 student what is occurring and why. C
3. A baseball is thrown straight up in the air, reaches its maximum height, and falls back down to the height from which it was originally thrown. What is the acceleration of the ball
   (a) halfway up to its maximum height?
   (b) at its maximum height?
   (c) halfway back down to the initial height from which it was thrown? T/I
4. A rubber ball is dropped from a height of 1.5 m. T/I
   (a) How long does it take to hit the ground?
   (b) What is the velocity of the ball when it has travelled a distance halfway to the ground?
5. An arrow is shot straight up into the air at 80.0 m/s. T/I
   (a) What is the arrow's maximum height?
   (b) How long does the arrow take to reach its maximum height?
   (c) Determine the total amount of time that the arrow is in the air.
6. A rock is thrown down from the top of a cliff with a velocity of 3.61 m/s [down]. The cliff is 28.4 m above the ground. Determine the velocity of the rock just before it hits the ground. T/I
7. Describe the motion of the object represented by the velocity–time graph in **Figure 4**. Give an example of an object that might undergo this type of motion. K/U

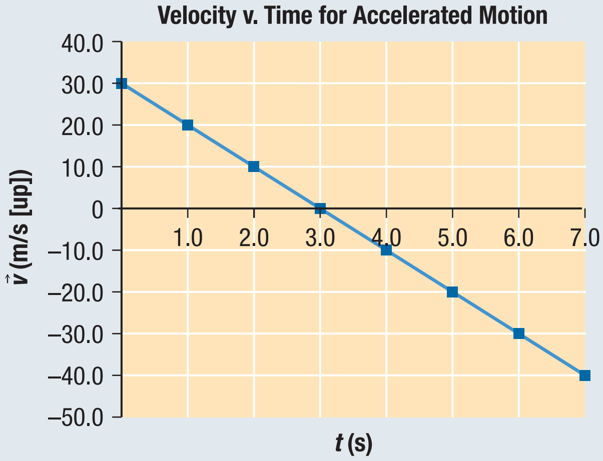


Figure 4

8. Research and describe a real-life situation where an object or person experiences an acceleration greater than g (9.8 m/s^2). A

GO TO NELSON SCIENCE

1.7 Explore an Issue in Vehicle Safety

SKILLS MENU

- Defining the Issue
- Researching
- Identifying Alternatives
- Analyzing
- Defending a Decision
- Communicating
- Evaluating

Electronic Speed Limiters for Teen Drivers

Today's automobiles are the safest vehicles ever. Advances in automotive technology have produced many safety devices, including seat belts, airbags, electronic stability control, electronic brake force distribution, and antilock brakes. All of these technologies are known to save lives when used correctly. Transport Canada indicates that, since 1987, the annual number of automobile accident fatalities in Canada has dropped by 33 %. If we are to decrease the number of automobile accidents even further, drivers will need to improve their safe driving practices. Statistics from the U.S. National Highway Traffic Safety Administration (NHTSA) show that teenage drivers are more likely to take driving risks, such as speeding, than older drivers. Speeding is a contributing factor in 30 % of all fatal crashes. Statistics also show that teens are less likely to wear seat belts than other drivers.

In addition to contributing to driving accidents, speed can affect the emissions released by vehicles as well as their efficiency. Automobile emissions make up a substantial portion of greenhouse gas emissions. Vehicle manufacturers have embraced advances in automobile technology to produce substantially more fuel-efficient vehicles. Even a highly fuel-efficient vehicle is at its most efficient when driven at a reduced speed. Transport Canada indicates that by reducing a vehicle's speed from 120 km/h to 100 km/h, fuel consumption could drop by as much as 20 %.

In Ontario and Québec, legislation has recently been passed to limit the speed of transport trucks to 105 km/h (**Figure 1**). A speed limiter is an electronic device that prevents a vehicle from travelling above a certain speed. This has been suggested as a way to increase highway safety and reduce the environmental impact of truck emissions. Some opponents of speed limiters say that the inability to go over a particular speed may prevent drivers from avoiding accidents. Others say that there is not enough evidence to prove that speed limiters actually prevent accidents, and that speed limiters can be tampered with.

Figure 1 Many truck drivers object to the use of devices to limit speeds, arguing that they will cause more frustration on the road.

The Issue

Suppose you are a member of the provincial student council association. The provincial government has tabled a bill that will call for the implementation of mandatory speed limiters for teenage drivers.

The government is proposing that all automobiles sold in Ontario have an electronic device installed that will

- electronically limit teen drivers to a maximum speed of 90 km/h
- sound an alarm when the vehicle reaches speeds of 60 km/h, 70 km/h, and 80 km/h

The provincial government has argued that installing these devices will increase highway safety, reduce automobile emissions, and protect new drivers. The provincial student council association will be making a presentation during a town hall meeting in which the proposed legislation is being discussed. Members of the Ontario Ministry of Transportation will be present.

ROLE

You will be acting as a member of the provincial student council association representing young drivers in Ontario.

AUDIENCE

Your audience will be the Ministry of Transportation but you will present your views at a town hall meeting where the speed limiter legislation is being discussed.

Goal

To convince the Ministry of Transportation to either

- support this bill in its current format
- recommend modifications to the bill
- not support the bill

Research

SKILLS HANDBOOK A5

Conduct library and Internet research about speed limiters and their effectiveness. Collect information about teen driving habits and their effect on road safety. You might conduct a survey among your fellow students for their opinions. You may wish to research the following:

- What positive effects have speed limiters had on safety among truck drivers?
- What negative effects have speed limiters had on safety?
- Would those who want to break the law be able to find a way to disable a speed limiter?

WEB LINK

To learn more about speed limiters,

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Identify Solutions

After reviewing your research, consider the impact the speed limiter bill could have on you and on the citizens of Ontario. What are the benefits and drawbacks of using speed limiters, and whom would they harm or benefit? What modifications to the bill might you recommend?

Make a Decision

Based on your research, decide which of the three possible solutions you will support. Alternatively, come up with a solution of your own.

Communicate

Prepare a position paper, photo essay, or other presentation format supporting your chosen decision. Be sure to support your decisions with research that will convince your audience (the Ministry of Transportation) to support your choice.

Plan for **Action**

This issue has the potential to affect you and your classmates for many years. Make a plan to make students aware of the potential for speed limiters that will electronically control driving behaviour among young drivers. Your plan should include an opportunity for young drivers to voice their opinions on this issue. For example, you might plan to start a group on a social networking site, or write an article for your school paper.

Investigation 1.2.1 OBSERVATIONAL STUDY

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Watch Your Speed

In this observational study, you will use very simple equipment to measure the speed of real-life objects.

Purpose

SKILLS HANDBOOK A2.4

In this study, you will use a stopwatch and a tape measure to determine the average speed of vehicles driving past your school. You will then determine the percentage of vehicles exceeding the posted speed limit.

Equipment and Materials

- 25 m–50 m tape measure
- stake or other marker
- stopwatch

Procedure

1. Choose a location near your school where vehicles will be travelling at what appears to be a constant speed. For example, be sure not to be close to a stop sign or stoplight.
2. Choose an obvious landmark such as a telephone pole as a starting point. Making sure that you stay off the road, measure a distance from your starting point for 10 m to 20 m along the curb. Mark the end of your known distance with a stake or other obvious object.
3. Stand well back from the curb before taking time measurements.

Do not stand on the road or too close to the curb for this study. Be aware of your surroundings and stay well away from the road at all times. Ensure you have your teacher's permission before performing this investigation.

4. Start your stopwatch as each vehicle passes the starting point, and stop the stopwatch as the vehicle passes the stake representing the end of your measured distance. Record your observations.
5. Use the defining equation for average speed, $v_{\text{av}} = \dfrac{\Delta d}{\Delta t}$, to determine the average speed of the vehicle.
6. Repeat this procedure for 50 vehicles.
7. Determine the speed limit in front of your school.
8. Calculate the percentage of vehicles passing your school that are exceeding the posted speed limit.

Analyze and Evaluate

SKILLS HANDBOOK A6.2

(a) Show one sample calculation determining the average speed of a vehicle. T/I C

(b) Plot the data you have gathered on a graph and analyze your results. Summarize your findings in a brief paragraph. Be sure to explain whether your data suggest that the speed limit near your school is being observed. T/I

(c) List any sources of uncertainty that may have affected your results. T/I

(d) If you were to perform this study again, what would you do to reduce the uncertainty? T/I

Apply and Extend

(e) Using the evidence gathered from this investigation, develop a road safety action plan that will help improve the level of road safety at your school. C

Investigation 1.4.1 OBSERVATIONAL STUDY

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Uniform Velocity

There are a number of devices and methods for collecting motion data in the laboratory, including tickertape devices, air tables, spark-gap timers, photogates, video analysis, and motion sensors. Tickertape devices, air tables, and spark-gap timers rely on generating a series of dots on either a paper tape or a paper sheet. These dots are generated at a constant rate and can be used to gather position–time data. Photogates, video analysis, and motion sensors use computer technology to collect and analyze real-time data.

A motion sensor is an ultrasonic transceiver. It transmits invisible ultrasonic waves into space. These waves are reflected from objects in their path back to the motion sensor's receiver. Computer software running on the interface, or on a computer to which the motion sensor is connected, is able to use these ultrasonic pulses to collect position–time data. Motion sensors and their associated software can be used to generate position–time, speed–time, and acceleration–time data and graphs. As an experimenter, you can choose which type of data to collect.

In this investigation you will use a motion sensor to collect position–time, velocity–time, and acceleration–time data for a motorized toy car as it moves across a horizontal lab bench.

Purpose

SKILLS HANDBOOK A2.4

To determine which type of motion (constant velocity, uniform acceleration, non-uniform acceleration) a motorized electric toy undergoes as it moves across a horizontal lab bench.

Equipment and Materials

- motion sensor
- computer or computer interface
- motorized toy car
- metre stick
- data storage device such as a USB drive (memory stick)
- graph paper (optional)

Procedure

1. Connect the motion sensor to a computer or computer interface.
2. Set the software or computer interface to collect position–time, velocity–time, and acceleration–time data (all three will be collected at once).
3. Turn on the toy car and hold it approximately 40 cm above the motion sensor.
4. Start collecting data with the motion sensor. You will hear a clicking sound and see a blinking light on the motion sensor.
5. Quickly place the toy car on the lab bench so that it is 15 cm in front of the motion sensor (**Figure 1**). (Most motion sensors cannot collect data when objects are placed less than 15 cm away from them.)

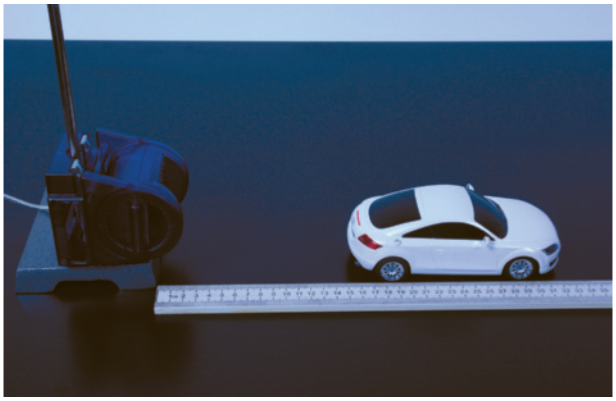

Figure 1 Positioning the car in front of the sensor

6. Allow the car to run approximately 2 m in a straight line away from the motion sensor.
7. Save your data. If necessary, export the data to a spreadsheet program.

Analyze and Evaluate

SKILLS HANDBOOK A6.5

(a) Generate full-page position–time, velocity–time, and acceleration–time graphs using graph paper or computer software. Describe the characteristics of each graph (for example, straight line, curve, increasing, decreasing, horizontal, zero or non-zero intercept value). T/I C

(b) What type of relationship is represented by each graph, linear or non-linear? T/I

(c) What type of motion is described by each graph? K/U

(d) Determine the slope of the position–time graph. How does this value compare to the data shown in the velocity–time graph? T/I C

(e) Determine the slope of the velocity–time graph. How does this value compare to the data shown in the acceleration–time graph? T/I C

(f) Calculate the area under the velocity–time graph. How does this value compare to the final position of your toy car? T/I C

(g) List any sources of uncertainty that may have affected your results. T/I

(h) If you performed this experiment again, what would you do to reduce the uncertainty in your measurements? T/I

Apply and Extend

(i) In this investigation you used graphical methods to analyze your data. Is it possible to use algebraic methods to determine the toy car's average speed? Explain your reasoning. T/I

(j) Perform research to determine how the technology you used in this investigation compares to sensors used in point-and-shoot digital cameras (**Figure 2**). How is it similar? How is it different? A

Figure 2 Many digital cameras use motion sensors.

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Investigation 1.4.2 OBSERVATIONAL STUDY

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Motion Down a Ramp

If you have ever been skiing or tobogganing, you know how thrilling motion can be when you are going down a hill or an incline. In this study you will use a motion sensor to collect position–time, velocity–time, and acceleration–time data for a PVC pipe as it rolls down a ramp. While the procedure you will use in this investigation is similar to that used in Investigation 1.4.1, you will find that your results are significantly different. You will find comparing results of the two investigations to be helpful for your analysis and evaluation.

Purpose

SKILLS HANDBOOK A2.4

To determine which type of motion (constant velocity, uniform acceleration, non-uniform acceleration) a PVC pipe will undergo when it rolls down an inclined ramp.

Equipment and Materials

- motion sensor
- computer or computer interface
- data storage device, such as a USB drive (memory stick)
- PVC pipe
- ramp, 1.5 m or longer
- textbooks or wood blocks
- metre stick
- masking tape
- graph paper (optional)

Procedure

1. Connect the motion sensor to a computer or computer interface.
2. Set the computer software or computer interface to collect position–time, velocity–time, and acceleration–time data (all three will be collected at once).
3. Use the books or wood blocks to incline the ramp to approximately 30°. Secure the motion sensor at the top of the inclined ramp with masking tape. Use a piece of masking tape to mark a point 15 cm in front of the motion sensor. Be sure to affix the masking tape in such a way that it will not interfere with the motion of your PVC pipe (**Figure 1**).

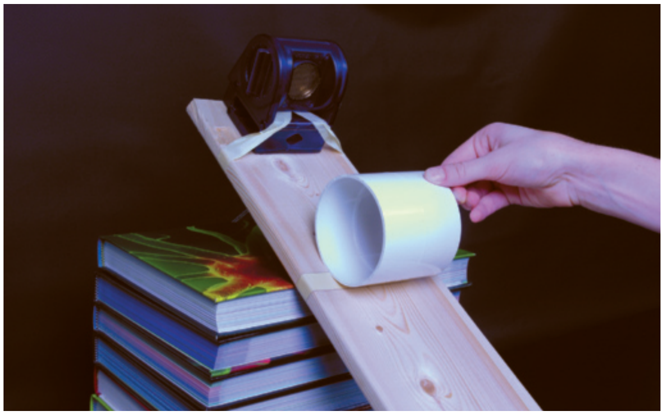


Figure 1 Positioning the PVC pipe on the ramp

4. Hold the PVC pipe on the ramp just below the masking tape 15 cm in front of the motion sensor. Be sure to hold the PVC pipe at rest.
5. Start collecting data with the motion sensor. You will hear a clicking sound and see a blinking light on the motion sensor.
6. Quickly release the PVC pipe and allow it to roll straight down the ramp. Catch the PVC pipe at the bottom of the ramp.
7. Save your data. If necessary, export the data to a spreadsheet before your analysis.

Analyze and Evaluate

SKILLS HANDBOOK A6.5

(a) Generate full-page graphs of the position–time, velocity–time, and acceleration–time data. Describe the characteristics of each graph (for example, straight line, curve, increasing, decreasing, horizontal, zero or non-zero intercept value). T/I C

(b) What type of relationship is represented in each graph, linear or non-linear? T/I

(c) What type of motion is described by each graph? K/U

(d) Determine the slope of the velocity–time graph. How does this calculated value compare to the data shown in your acceleration–time graph? T/I C

(e) Calculate the area under the acceleration–time graph. How does this calculated value compare to the final velocity of the PVC pipe? T/I C

(f) List any sources of uncertainty that may have affected your results. T/I

(g) If you were able to perform this study again, what could you do to reduce the uncertainty? T/I

Apply and Extend

(h) Repeat this investigation using remote control vehicles. Generate data that show constant velocity and uniform acceleration. Compare the acceleration of different brands and models of remote control vehicles. T/I C

(i) Repeat this experiment by rolling the PVC pipe up the inclined ramp. Be sure not to push the pipe hard enough to physically hit the motion sensor. How do the data collected for this investigation compare to the data collected in the original investigation? T/I C

(j) Roller coasters are some of the most exciting thrill rides available. Modern roller coasters twist, turn, and spiral in a complex and thrilling way. Old-fashioned roller coasters like the Mighty Canadian Minebuster at Canada's Wonderland are wooden and do not spiral but can still make for an exciting ride (**Figure 2**). Use the knowledge you gained from this investigation, and any personal life experiences, to help you write a letter to your younger sister explaining which part of an old-fashioned roller coaster ride is the most exciting, which part is the least exciting, and why. T/I C

Figure 2 What makes a roller coaster ride like this exciting?

CHAPTER 1 SUMMARY

Summary Questions

1. Create a study guide based on the Key Concepts on page 6. For each point, write a brief letter to a friend explaining the mentioned concept(s), create a solved sample review problem, draw a labelled diagram, or create a mind map.
2. Look back at the Starting Points questions on page 6. Answer these questions using what you have learned in this chapter. Compare your latest answers with those that you wrote at the beginning of the chapter. Note how your answers have changed.

Vocabulary

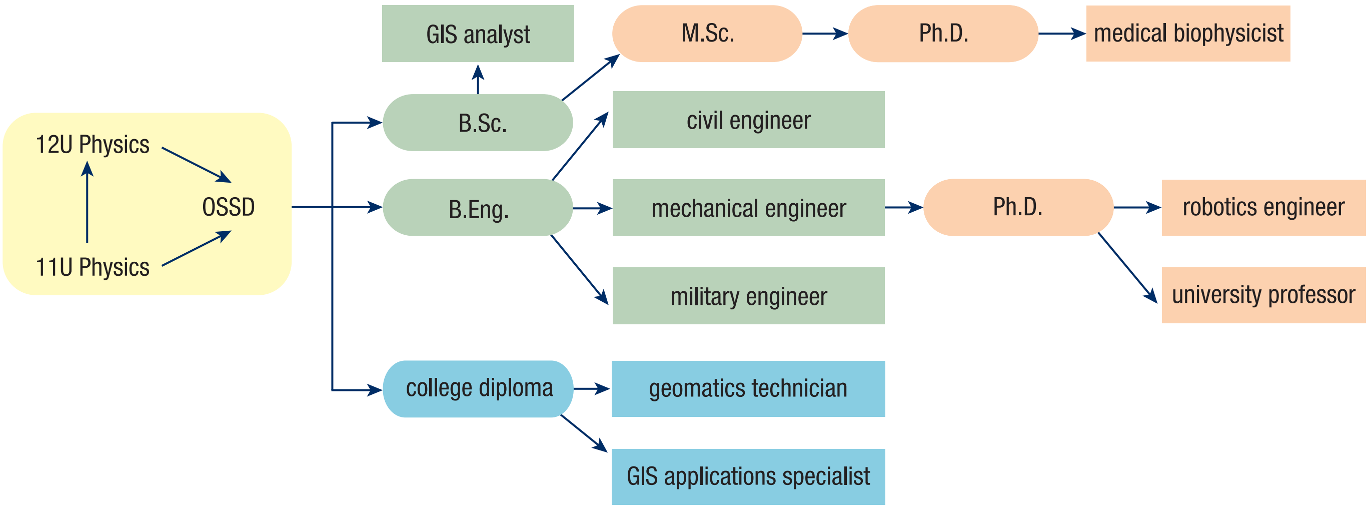
kinematics (p. 8)
motion (p. 8)
distance (d) (p. 8)
direction (p. 8)
scalar (p. 9)
vector (p. 9)
position ($\vec{d}$) (p. 9)
displacement ($\Delta\vec{d}$) (p. 9)
vector scale diagram (p. 11)
directed line segment (p. 11)
average speed (v_{av}) (p. 14)
average velocity ($\vec{v}_{av}$) (p. 16)
position–time graph (p. 16)
slope (m) (p. 16)
rise (p. 16)
run (p. 16)
motion with uniform or constant velocity (p. 18)
motion with non-uniform velocity (accelerated motion) (p. 18)
acceleration ($\vec{a}_{av}$) (p. 21)
velocity–time graph (p. 21)
motion with uniform acceleration (p. 27)
instantaneous velocity ($\vec{v}_{inst}$) (p. 27)
acceleration–time graph (p. 31)
acceleration due to gravity (g) (p. 40)
free fall (p. 40)
terminal velocity (p. 43)

CAREER PATHWAYS

SKILLS HANDBOOK A7

Grade 11 Physics can lead to a wide range of careers. Some require a college diploma or a bachelor of science degree. Others require specialized or post-graduate degrees. This graphic organizer shows a few pathways to careers related to topics covered in this chapter.

1. Select a career from the graphic organizer below or another career that interests you that relates to what you have learned in this chapter. Perform research to determine what kind of education or work experience is required for this career. Is there more than one pathway to this career? Summarize your findings and share them with a classmate.


12U Physics
11U Physics
OSSD
B.Sc.
B.Eng.
college diploma
GIS analyst
M.Sc.
Ph.D.
medical biophysicist
civil engineer
mechanical engineer
Ph.D.
robotics engineer
university professor
military engineer
geomatics technician
GIS applications specialist

GO TO NELSON SCIENCE

CHAPTER 1 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. Which of the following is the term for the line an object moves along from a particular starting point? (1.1) K/U
   (a) motion
   (b) distance
   (c) position
   (d) direction
2. Which of the following terms is used to describe a quantity that has only magnitude? (1.1) K/U
   (a) scalar
   (b) position
   (c) directed line segment
   (d) vector
3. If you walk 450 m north and then 200 m south, what is your displacement? (1.1) K/U
   (a) 250 m
   (b) 250 m north
   (c) 650 m
   (d) 650 m north
4. Which of the following is a description of a vector quantity? (1.1) K/U
   (a) A rock rolls 3 m.
   (b) A plane flies 600 km west.
   (c) A fish swims at 3 m/s.
   (d) A runner jogs for 30 min.
5. Which of the following terms means the change between points on the *x*-axis? (1.2) K/U
   (a) steepness
   (b) slope
   (c) run
   (d) rise
6. A jogger runs 5.0 km in 33 min. What is the speed of the jogger? (1.2) T/I
   (a) 0.15 m/s
   (b) 2.5 m/s
   (c) 0.25 m/s
   (d) 2.8 m/s
7. Which of the following is the correct expression for average acceleration? (1.3) K/U
   (a) $\dfrac{\Delta\vec{d}}{\Delta t}$
   (b) $\dfrac{\Delta t}{\Delta v}$
   (c) $\dfrac{\Delta\vec{v}}{\Delta t}$
   (d) $\dfrac{\Delta t}{\Delta\vec{v}}$
8. A car starts from rest and speeds up to 15 m/s in 5.0 s. What is the acceleration of the car? (1.3) T/I
   (a) 65 m/s^2
   (b) 6.5 m/s^2
   (c) 3.3 m/s^2
   (d) 3.0 m/s^2

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

9. Position is the distance of an object from a particular reference point. (1.1) K/U
10. Vector scale diagrams show the vectors associated with a displacement, drawn to a particular scale. (1.1) K/U
11. The displacement of an object is found by adding the start position and the end position. (1.1) K/U
12. The average acceleration of an object in motion is its total displacement divided by the total time taken for the motion. (1.2) K/U
13. Motion with constant velocity is called accelerated motion. (1.2) K/U
14. The slope of a velocity–time graph gives the acceleration of the object. (1.3) K/U
15. Instantaneous velocity is the velocity of an object over a time range. (1.3) K/U
16. The area under an acceleration–time graph gives the average velocity of that time period. (1.4) K/U
17. Terminal velocity results from air resistance that exerts a force on a falling object that is equal to the force of gravity. (1.6) K/U

To do an online self-quiz,

GO TO NELSON SCIENCE

CHAPTER 1 REVIEW

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

Knowledge

For each question, select the best answer from the four alternatives.

1. Which of the following terms refers to the total length of the path travelled by an object in motion? (1.1) K/U
   (a) kinematics
   (b) distance
   (c) direction
   (d) position
2. Which of the following terms means the change in position of an object? (1.1) K/U
   (a) acceleration
   (b) direction
   (c) displacement
   (d) vector
3. What is your displacement if you walk 250 m east and then 100 m west? (1.1) K/U
   (a) 100 m [W]
   (b) 150 m [W]
   (c) 300 m [E]
   (d) 150 m [E]
4. Which of the following describes a vector quantity? (1.1) K/U
   (a) An apple falls 6 m.
   (b) A fish swims at 1 m/s.
   (c) A student solves a puzzle in 10 min.
   (d) A car drives 60 km north.
5. Which of the following describes a line drawn to a specific scale with an arrow head? (1.1) K/U
   (a) directed line segment
   (b) position
   (c) motion
   (d) vector scale diagram
6. What is the correct expression for average velocity? (1.2) K/U
   (a) $\frac{\Delta d}{\Delta t}$
   (b) $\frac{\Delta t}{\Delta d}$
   (c) $\frac{\Delta \vec{d}}{\Delta t}$
   (d) $\frac{\Delta t}{\Delta \vec{d}}$
7. Which of the following terms refers to the change between points on the *y*-axis? (1.2) K/U
   (a) rise
   (b) run
   (c) slope
   (d) steepness
8. Which of the following objects most accurately demonstrates an object moving with uniform velocity? (1.2) K/U
   (a) a merry-go-round
   (b) a runner racing from start to finish
   (c) a tennis ball during a match
   (d) a car travelling on the highway with cruise control on
9. A car starts from rest and speeds up to 10.0 m/s in 4.0 s. What is the acceleration of the car? (1.3) T/I
   (a) 40 m/s^2
   (b) 25 m/s^2
   (c) 2.5 m/s^2
   (d) 2.0 m/s^2

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

10. Motion is the line an object moves along from a particular starting point. (1.1) K/U
11. A scalar is a quantity that has a magnitude and also direction. (1.1) K/U
12. Kinematics is the term used by physicists and engineers to describe the study of how objects move. (1.1) K/U
13. Vectors are added by joining them tip to tip. (1.1) K/U
14. The difference between speed and velocity is that speed is a vector while velocity is a scalar. (1.2) K/U
15. The slope of a position–time graph gives the velocity of the object. (1.2) K/U
16. Motion in a straight line but with a varying speed is considered motion with uniform velocity. (1.2) K/U
17. The slope of a velocity–time graph gives the displacement of an object. (1.3) K/U
18. Acceleration is measured in metres per second, per second. (1.3) K/U

Match each term on the left with the most appropriate description on the right.

19.

(a)	distance	(i)	a quantity that has a magnitude only
(b)	scalar	(ii)	motion at a constant speed in a straight line
(c)	acceleration	(iii)	the acceleration of an object in free fall
(d)	uniform velocity	(iv)	the steepness of a line or rise over run
(e)	acceleration due to gravity	(v)	the total length of the path travelled by an object
(f)	slope	(vi)	the rate of change of velocity (1.1, 1.2, 1.3, 1.6) K/U

Write a short answer to each question.

20. In your own words, describe the difference between velocity and speed and how they relate to distance and displacement. (1.1, 1.2) K/U C

21. In your own words, describe what it means for an object to have a negative acceleration. (1.3) K/U C

Understanding

Use **Figure 1** to answer Questions 22 to 25.

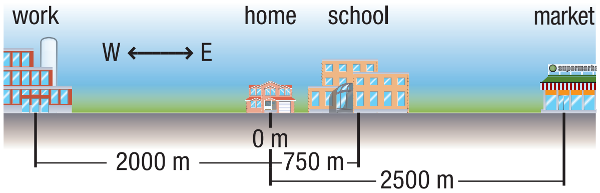


Figure 1

22. If you were to walk from home to work, what would your displacement be? (1.1) T/I

23. What is your displacement if you walk from school to the market? (1.1) T/I

24. You have to go to the market one evening after work to pick up food for supper. What is your displacement from work to the market? (1.1) T/I

25. After school, you have to go to the market before returning home. What is your total displacement? (1.1) T/I

26. A car changes its position from 76 km [W] to 54 km [E]. What is the car's displacement? (1.1) T/I

27. A race car travels a distance of 250 m in 4.0 s. What is the average speed of the car? (1.2) K/U

28. A person throws a baseball with an average speed of 15 m/s. How far will the ball go in 3.0 s? (1.2) K/U

29. A bird flies 310 m [S] of its nest in 8.0 s. What is the velocity of the bird? (1.2) T/I

30. A car starts at 45 km [W] of a railroad crossing and travels to 15 km [E] of the railroad in 1.2 h. What is the velocity of the car in metres per second? (1.2) T/I

31. A bird flies from its nest and lands in a tree that is 2400 m due west. If the bird can fly at an average velocity of 9.0 m/s, for how long, in seconds, is the bird in flight? (1.2) T/I

32. A drag racer completes a race in 14.3 s. If the drag racer has an average speed of 251 km/h, how long is the racetrack? (1.2) T/I

33. (a) For the position–time graph shown in **Figure 2**, explain whether the object being described has uniform or non-uniform velocity.
    (b) Relative to the object's displacement, is the velocity positive or negative? If applicable, how is the velocity changing? Explain. (1.2) K/U

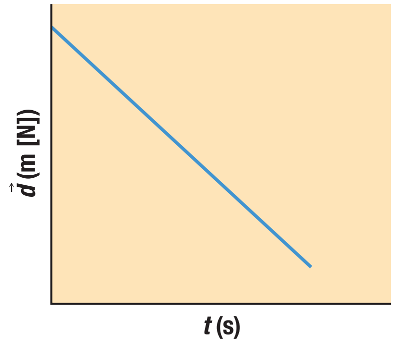


Figure 2

34. (a) For the position–time graph shown in **Figure 3**, explain whether the object being described has uniform or non-uniform velocity.
    (b) Relative to the object's displacement, is the velocity positive or negative? If applicable, how is the velocity changing? Explain. (1.2) K/U

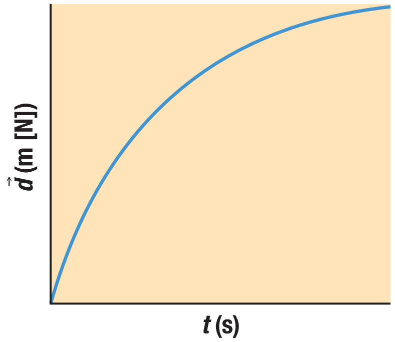


Figure 3

35. A runner starts a race and in 1.25 s has a velocity of 5.0 m/s [E]. Determine the acceleration of the runner. (1.3) T/I

36. A horse starts running and accelerates at a rate of 6.25 m/s^2 [W] for 2.0 s. What is the final velocity of the horse? (1.3) T/I

37. How long does it take a bullet to accelerate from rest to a speed of 343 m/s if the blast from the gun can accelerate the bullet at a rate of 1.25×10^5 m/s^2? (1.3) T/I

38. A race car slows down to make a turn. If it has an initial velocity of 180 km/h [S] and accelerates at a rate of 8.2 m/s^2 [N] for 3.2 s, at what velocity (in kilometres per hour) does the race car make the turn? (1.3) T/I

39. A student riding a bicycle begins to go downhill and accelerates at a rate of 1.8 m/s^2. If the acceleration lasts for 2.4 s, and the final speed of the student on the bicycle is 10.2 m/s, at what speed was he initially travelling? (1.3) T/I

40. **Figure 4** is a velocity–time graph for an object moving with constant acceleration. Determine the displacement of the object over the interval 0 s to 4.0 s. (1.4, 1.5) T/I

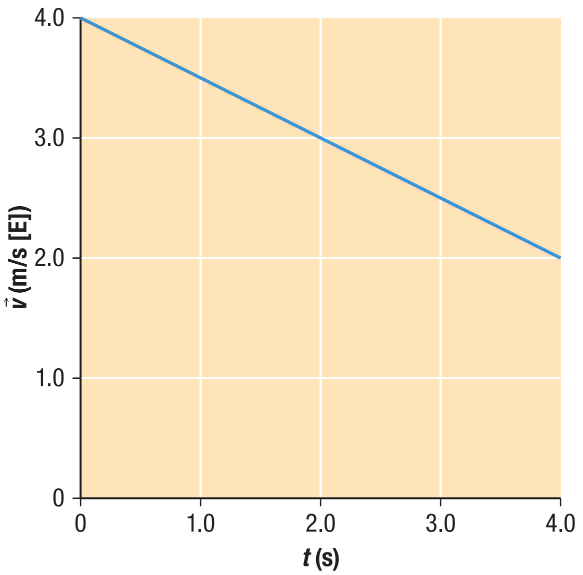


Figure 4

41. An object starts with an initial velocity of 4.0 m/s [W] and has an acceleration of 1.0 m/s^2 [W]. What is the displacement of the object after 3.0 s? (1.5) T/I

42. Students roll a ball down a hill with an initial velocity of 3.0 m/s. The ball accelerates at a rate of 0.80 m/s^2 and rolls a total distance of 6.0 m down the hill. (1.5) T/I
    (a) The students do not have a stopwatch. What formula would be useful to find the final velocity?
    (b) What is the final velocity of the ball?

43. Students performing an experiment for their physics class are dropping balls from a height of 10.0 m. Ignore air resistance. (1.6) T/I
    (a) How long does it take for a ball to hit the ground?
    (b) What is the final velocity of the ball just before it hits the ground?

Analysis and Application

44. A car drives 230 m [E] to a traffic light. It then continues on for another 350 m [E]. (1.1) T/I C
    (a) Draw a vector scale diagram to represent the displacement of the car.
    (b) Calculate the car's total displacement.

45. An eagle perched on a branch flies 54 m [N] to catch a fish and then flies 72 m [S] back to its nest. (1.1) T/I C
    (a) Draw a vector scale diagram to represent the displacement of the eagle.
    (b) Calculate the eagle's total displacement.

46. The position of an object changes from 4.0 m [E] of its starting point to 16 m [E] of its starting point in 6.0 s. What is the velocity of the object? (1.2) T/I

47. Fifteen seconds into a car race, a car runs through a checkpoint that is 250 m [N] from the starting point. Thirty-six seconds into the race it runs through another checkpoint that is 750 m [N] from the starting point. Determine the average velocity of the car between the two checkpoints. (1.2) T/I

48. A motocross racer hits a checkpoint 25 s into a race that is 320 m [E] from the starting point. At the checkpoint, the racer takes a sharp turn, and at 49 s into the race hits another checkpoint that is 140 m [W] from the starting line. What is the average velocity of the racer between the two checkpoints? (1.2) T/I

49. A train starts out at a station that is 450 km west of a city and travels to the next station, which is 920 km west of the city. If the train has an average velocity of 40.0 km/h, how long does it take to travel between the two stations? (1.2) T/I

50. A man has to drive from his job, which is 4.5 km south of his home, to the grocery store, which is 2.5 km north of his home. If he drives with an average speed of 9.7 m/s, how long, in minutes, will the trip take him? (1.2) T/I

51. A deer walking through the forest gets scared and begins to run away. If the walking speed of the deer is 1.0 m/s and its running speed is 7.6 m/s, and it only takes the deer 0.80 s to change its speed, what is the acceleration of the deer? (1.3) T/I

52. How long does it take a motorcycle to change its speed from 7.0 m/s [W] to 12.1 m/s [W] if it can accelerate at a rate of 3.9 m/s^2 [W]? (1.3) T/I

53. A bungee jumper is falling at a velocity of 32.0 m/s when the cord catches and begins to accelerate her upward. Then, 5.30 s after the cord catches, she has a velocity of 24.0 m/s upward. What is the average acceleration due to the pull of the bungee cord and in which direction is it applied? (1.3) T/I

54. The wind is blowing a balloon at a velocity of 4.3 m/s [W]. After 7.2 s, the wind blows the balloon with a velocity of 2.5 m/s [E]. Determine the average acceleration of the balloon. (1.3) T/I

55. Students decide to roll a ball between two hills and take measurements of its velocity. These measurements are plotted in **Figure 5**. (1.3) T/I C

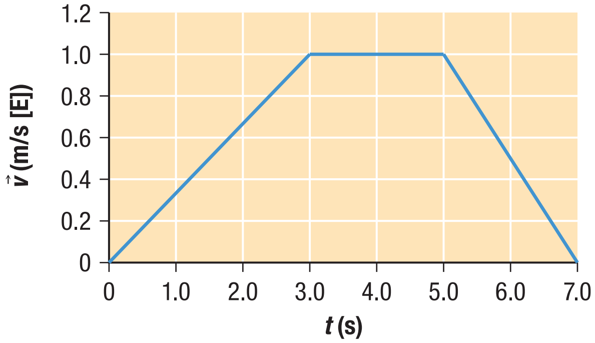


Figure 5

(a) Determine the average acceleration over the following time intervals: 0 s to 3.0 s and 3.5 s to 5.0 s.

(b) Determine the total displacement over the time interval 0 s to 7.0 s.

56. **Figure 6** is an acceleration–time graph for an object. (1.4) T/I

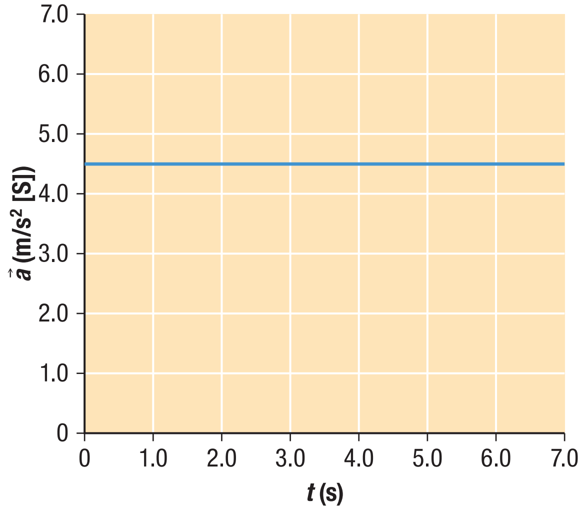


Figure 6

(a) Calculate the change in velocity over the time interval 2.0 s to 5.0 s.

(b) If the starting velocity for the time interval in (a) is 6.0 m/s [S], what is the final velocity of the object at the end of the time interval?

57. (a) Using the acceleration–time graph shown in **Figure 7**, create a table calculating the velocity at 1.0 s intervals given that the initial velocity of the object described is 5.0 m/s [E].

(b) Use what you found in (a) to draw the velocity–time graph. (1.3, 1.4) T/I C

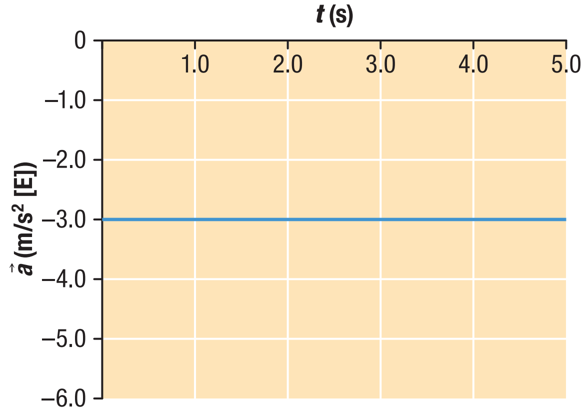


Figure 7

58. Consider the position–time graph shown in **Figure 8**. (1.4) T/I

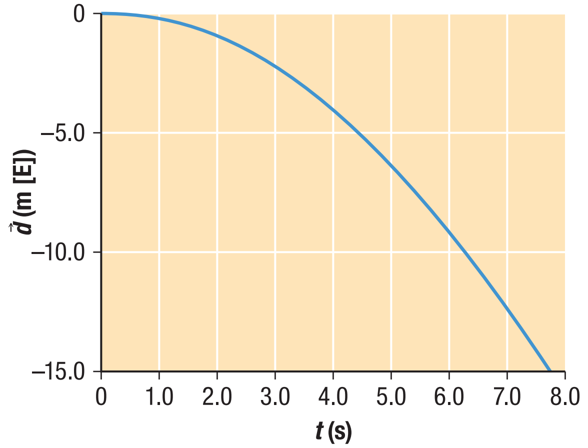


Figure 8

(a) What is the position of the object at $t = 3.0$ s?

(b) Estimate the instantaneous velocity of the object at $t = 2.0$ s.

(c) What is the average velocity for the object from 1.0 s to 5.0 s?

59. A car company is performing brake tests on one of its cars. The car reaches a speed of 160 km/h and then hits the brakes to slow down at a rate of 11.0 m/s^2. (1.5) T/I

(a) How long does it take the car to stop?

(b) How far does the car travel when braking?

60. A sailboat accelerates uniformly from 5.5 m/s to 9.0 m/s over a distance of 32 m. At what rate is the boat accelerating? (1.5) T/I

61. A van merges onto a highway on-ramp with a velocity of 52 km/h and accelerates at a rate of 2.0 m/s^2 for 7.2 s. (1.5) T/I
    (a) What is the displacement of the van over this time?
    (b) What is the final velocity of the van?

62. Draw velocity–time and position–time graphs for the following situations. Use up as positive and ignore air resistance. (1.4, 1.6) T/I C
    (a) A boy throws rocks with an initial velocity of 12 m/s [down] from a 20 m bridge into a river. Consider the river to be at a height of 0 m.
    (b) A baseball player hits a ball straight up with an initial velocity of 32 m/s. Use a time interval from the hit until the ball hits the ground.

63. A student is throwing rocks off of a bridge straight down into a river below. If he throws a rock with an initial speed of 10.0 m/s and it takes the rock 2.1 s to hit the water, how high is the bridge? Ignore air resistance. (1.6) T/I

64. A baseball player throws a ball into the air with an initial speed of 22 m/s [up]. Ignore air resistance. (1.6) T/I
    (a) How high does the ball go?
    (b) How long is the ball in the air before she catches it?

Evaluation

65. (a) Using a metre stick or another suitable measuring device, drop a pencil from 1.0 m and use a stopwatch to time how long it takes to hit the ground. Repeat this three times and create a table of your results. Determine the average velocity in each case.
    (b) Repeat (a), but this time drop the pencil from 2.0 m. Which distance gives the fastest average velocity? Is this what should be expected? Explain. (1.2, 1.3) T/I C A

66. Compare the position–time graphs in **Figure 9.** Which graph has the greatest acceleration in magnitude? Explain how you know. (1.4) T/I C

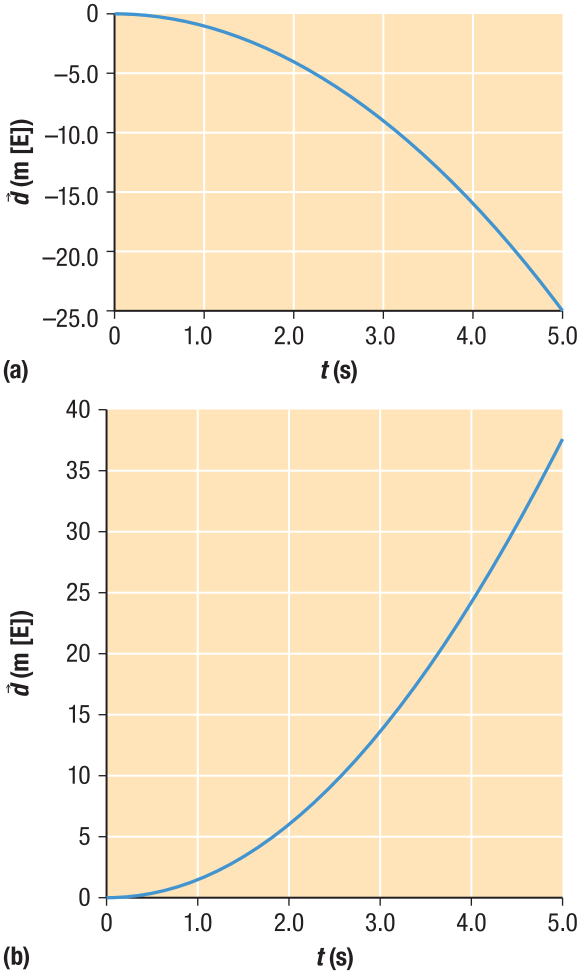


Figure 9

67. An object moves according to the velocity–time graph in **Figure 10**. (1.1, 1.2, 1.3, 1.4) T/I C A

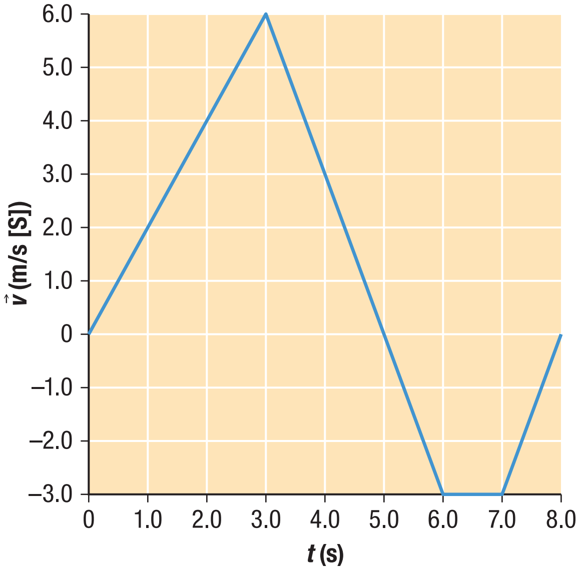


Figure 10

(a) What is the average acceleration over the interval 0 s to 2.0 s? What is the acceleration from 3.0 s to 6.0 s?

(b) In your own words, describe what it means to have a negative velocity. For this object, for what time interval is the velocity negative?

(c) State the intervals for when the motion of the object fits the following categories:
  (i) Positive velocity and negative acceleration
  (ii) Negative velocity and positive acceleration
  (iii) Zero acceleration

(d) Describe in your own words how you would find the total distance that the object travelled from its starting position. How would this differ if you were trying to find the position of the object relative to its starting position?

(e) Calculate both the total distance the object travelled and its position relative to its starting point over the interval 0 s to 8.0 s.

68. Consider the position–time graph shown in **Figure 11**. (1.3, 1.4) T/I C A

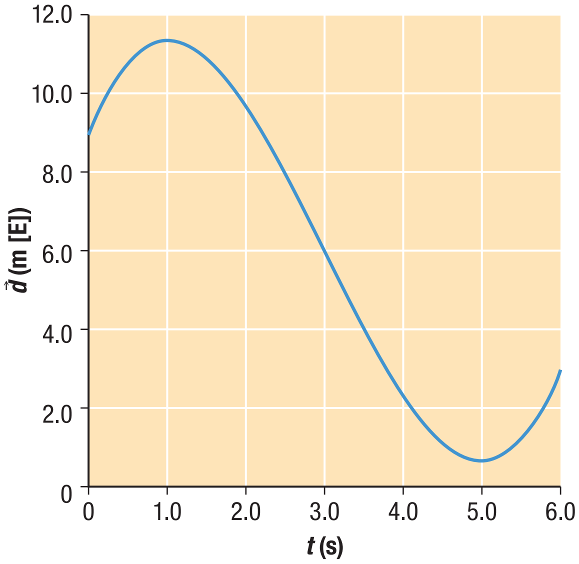


Figure 11

(a) At what times is the instantaneous velocity of the object being described zero? Explain.

(b) Describe how you would determine where the instantaneous acceleration is zero given a velocity–time graph. How would the graph look at these points?

(c) Use the graph to approximate where the instantaneous acceleration is zero. If necessary, sketch a velocity–time graph to help.

(d) What happens to the graph at the point found in (c)? Are there any defining characteristics of the graph at this point?

Reflect on Your Learning

69. When considering velocity–time graphs, we know that the area underneath the line or curve gives the displacement of an object. The slope between two points on the line or curve gives the average acceleration over that time interval. T/I C A

  (a) Using this as an analogy, describe in your own words how to find the velocity from an acceleration–time graph. How would the velocity–time graph look if the acceleration–time graph was not constant?

  (b) What might the slope between two points on the acceleration–time curve represent?

Research

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70. Since the beginning of human exploration, leaders, merchants, and adventurers alike have been using evolving methods to determine their relative positions and navigate the land. Research one or two early methods of mapmaking or navigation and write a page describing their history. When writing, consider the following questions to help guide you: What mathematical knowledge was necessary? What devices or instruments were necessary and how were they invented? Were there any devices or discoveries that made this method obsolete? T/I C A

71. (a) Research the world's fastest land animals and write a paragraph or two comparing their speeds, how they move, and any limits on how long this speed can be maintained.

  (b) Research the world's fastest and longest-flying animals and write a paragraph or two comparing their speeds, how they move, and any limits on how long this speed can be maintained.

  (c) Research the world's fastest swimming animals and write a paragraph or two comparing their speeds, how they move, and any limits on how long this speed can be maintained. T/I C A

72. Human innovation is constantly leading to new and improved technology, and this is especially true when it comes to transportation and speed. Write a one-page report or prepare a poster comparing the fastest vehicles in the categories of land speed, air speed, and space shuttle travel. T/I C A

73. Many technologies apply concepts related to kinematics; for example, technologies used to monitor false starts in a sprint competition. Research this technology, and describe how it works. T/I C A

CHAPTER 2 Motion in Two Dimensions

KEY CONCEPTS

After completing this chapter you will be able to

- explain the difference between vectors and scalars
- solve vector problems involving distance, position, and displacement
- describe how to determine total displacement in two dimensions by scale diagram and by the component method
- solve problems related to the horizontal and vertical components of motion of a projectile using kinematics equations (determine the range, maximum height, and time of flight for a projectile's motion)
- assess the social and environmental impacts of a technology that applies kinematics concepts

How Are Two-Dimensional Motions Determined?

Throughout its history, Canada has been known for its vast wildlife population. Global warming and human activity, however, have had a negative impact on many of Canada's wildlife species. The U.S. Geological Survey predicts that by 2050 Canada's polar bear population will be only one-third of its current level. Scientists have turned to global positioning system (GPS) technology to help them better understand the impact that climate change is having on many species. GPS is a navigational system that was originally created by the U.S. Department of Defense. It consists of a series of satellites and ground stations that emit or relay signals that can be detected by receivers on Earth. The precise position of each satellite and ground station is known. A GPS receiver receives signals from multiple satellites or ground stations. The GPS receiver uses their vector positions to triangulate its own location anywhere on Earth's surface to within a few metres.

GPS technology has allowed scientists to precisely track the migratory routes of caribou, polar bears, wolves, and many other types of animals. The Northwest Territories' Central Arctic Wolf Project had been tracking a male wolf named Brutus and his pack in their travels across Canada's Ellesmere Island. Regardless of weather conditions or the time of day, Brutus's GPS tracking collar sent position data to scientists every 12 h. On one trip the pack was measured travelling 129 km in 84 h. From the data gathered, scientists were able to determine when the pack was hunting successfully, tracking herds, resting, and even when young wolves were being born. By analyzing GPS data, scientists were also able to determine where and when Brutus was eventually killed by a musk ox. By tracking animal movements, we can learn more about how they use their natural habitat and how they are adapting to environmental changes due to climate change. GPS technology applies concepts related to motion in two dimensions. You will learn more about these concepts in this chapter.

STARTING **POINTS**

Answer the following questions using your current knowledge. You will have a chance to revisit these questions later, applying concepts and skills from the chapter.

1. (a) Using a directional compass and four sticky notes, place the labels North, South, East, and West near the edges of a desk.
   (b) Place two small objects, such as a penny and a nickel, on the desk. One of these two objects should be at the centre of the desk.
   (c) Place the eraser end of a pencil next to one of the objects, and rotate the sharpened end of the pencil to point toward the other object. Using compass directions and a protractor, describe the direction in which your pencil is pointing. Be as precise as possible.
   (d) Move the object that is not at the centre of the desk to a different position and repeat (c).
   (e) Compare your method of describing the direction from one object to the other with methods used by some of your classmates.
2. Describe how you could change how you throw a ball so that it travels a greater horizontal distance.
3. Describe how you could change how you throw a ball so that it reaches a greater height at the top of its flight.
4. Describe how you could change how you kick a ball so that it is in the air for a longer time.

Mini Investigation

Garbage Can Basketball

Skills: Performing, Observing, Analyzing

If you have ever thrown a ball to another person while playing catch, you probably have some idea of how the ball (projectile) will move. You think about how hard and at what angle you should throw the ball so that it reaches the catcher. This activity will give you an opportunity to test your intuitive understanding of how a projectile will move when launched into the air, by comparing your understanding with reality in a number of different situations.

Equipment and Materials: small garbage can; sheet of used paper

1. Place the garbage can on the floor a set distance away.
2. Crumple a sheet of used paper into a ball and try to throw it into the garbage can. Continue your trials until you are successful.
3. Try Step 2 again, but release the ball of paper at knee level.
4. Repeat Step 2, but this time release the ball of paper at waist level.
5. Repeat Step 2, but this time release the ball of paper at shoulder level.

A. Describe how your launching techniques in Steps 3 to 5 were different. That is, how did you throw the ball of paper differently from different heights so that it landed in the garbage can? T/I C

2.1 Motion in Two Dimensions— A Scale Diagram Approach

Figure 1 The motion of these cyclists is two-dimensional in the plane of the road.

Many of the moving objects that you observe or experience every day do not travel in straight lines. Rather, their motions are best described as two-dimensional. When you pedal a bicycle around a corner on a flat stretch of road, you experience two-dimensional motion in the horizontal plane (**Figure 1**).

Think about what happens when a leaf falls from a tree. If the leaf falls on a day without any wind, it tends to fall straight down to the ground. However, if the leaf falls on a windy day, it falls down to the ground and away from the tree. In this case, the leaf experiences two different motions at the same time. The leaf falls vertically downward due to gravity and horizontally away from the tree due to the wind. We say that the leaf is moving in two dimensions: the vertical dimension and the horizontal dimension. In Chapter 1, we analyzed the motion of objects that travel in only one dimension. To fully describe the motion of a leaf falling in the wind, and other objects moving in two dimensions, we need strategies for representing motion in two dimensions.

In Chapter 1, we analyzed the motions of objects in a straight line by studying vector displacements, velocities, and accelerations. How can we extend what we have already learned about motion in one dimension to two-dimensional situations? This is the question that we will pursue throughout this chapter.

CAREER **LINK**

Naval officers use gyroscopic compasses and satellite navigation to navigate Canada's naval fleet. However, every Canadian MARS (Maritime Surface and Subsurface) Officer still needs to know how to navigate the old-fashioned way, using a sharp pencil, a parallel ruler, and a protractor. It is essential for Canada's naval officers to have an extensive knowledge of vectors to safely navigate Canada's coastal waters and the high seas. To learn more about becoming a naval officer,

GO TO NELSON SCIENCE

Direction in Two Dimensions: The Compass Rose

The compass rose, shown in **Figure 2**, has been used for centuries to describe direction. It has applications on land, on the sea, and in the air. Recall that when we draw vectors, they have two ends, the tip (with the arrowhead) and the tail. In **Figure 3**, the vector that is shown pointing east in Figure 2 is rotated by 20° toward north. We will use a standard convention for representing vectors that point in directions between the primary compass directions (north, south, east, and west) to describe the direction of this vector. Figure 3 shows how the convention can be applied to this vector.

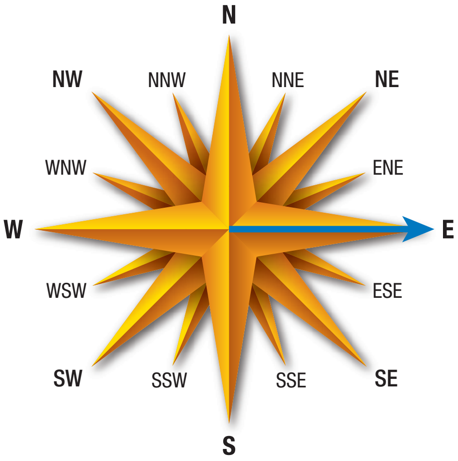

Figure 2 Compass rose, showing a vector pointing due east

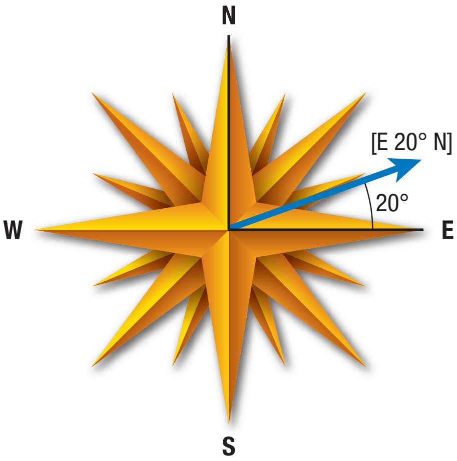

Figure 3 Convention for describing vector directions

We write the rotated vector's direction as [E 20° N]. This can be read as "point east, and then turn 20° toward north." Notice that in Figure 3 the complementary angle is 70°. Recall that complementary angles are two angles that add to 90°. So, another way of describing this vector's direction is [N 70° E], which can be read as "point north, and then turn 70° toward east." Both directions are the same, and the notation is interchangeable. The other important convention we will use is that, when using a Cartesian grid, north and east correspond to the positive y-axis and the positive x-axis, respectively.

When we are adding vectors in two dimensions, the vectors will not always point due north, south, east, or west. Similarly, the **resultant vector**—the vector that results from adding the given vectors—often points at an angle relative to these directions. So it is important to be able to use this convention to describe the direction of such vectors. In Tutorial 1, we will practise creating scale drawings of given vectors by choosing and applying an appropriate scale. In a scale such as 1 cm : 100 m, think of the ratio as "diagram measurement to real-world measurement." So a diagram measurement of 5.4 cm = 5.4 × (1 cm) represents an actual measurement of 5.4 × (100 m) = 540 m. You may find using a table like **Table 1** to be helpful.

resultant vector a vector that results from adding two or more given vectors

Table 1 Scale Conversions

	Given	Given	Required
Variable	Δd_1	Δd_2	Δd_T
before conversion (100 m)	540 m		
after conversion (1 cm)	5.4 cm		

Tutorial 1 Drawing Displacement Vectors in Two Dimensions Using Scale Diagrams

When drawing two-dimensional vectors, we must take not only the magnitude of the vector into consideration but also its direction. To draw two-dimensional vectors using a scale diagram, we need to determine a reasonable scale for the diagram. Scale diagrams should be approximately one half page to one full page in size. Generally speaking, the larger the diagram, the better your results will be.

Sample Problem 1: Draw a Displacement Vector to Scale

Draw a scale diagram of a displacement vector of 41 m [S 15° W].

Given: $\Delta\vec{d} = 41$ m [S 15° W]

Required: Scale diagram of $\Delta\vec{d}$

Analysis: Choose a scale, and then use it to determine the length of the vector representing $\Delta\vec{d}$.

Solution: It would be reasonable to choose a scale of 1 cm : 10 m (each centimetre represents 10 m). Convert the displacement vector to the appropriate length using the following conversion method:

$$\Delta\vec{d} = (41\ \cancel{\text{m}})\left(\frac{1\ \text{cm}}{10\ \cancel{\text{m}}}\right)\ [\text{S } 15^\circ\ \text{W}]$$

$$\Delta\vec{d} = 4.1\ \text{cm}\ [\text{S } 15^\circ\ \text{W}]$$

In **Figure 4**, the vector is drawn with a magnitude of 4.1 cm. The direction is such that it originally pointed south and then was rotated 15° toward west.

Statement: At a scale of 1 cm : 10 m, the given displacement vector is represented by $\Delta\vec{d} = 4.1$ cm [S 15° W], as drawn in the diagram.

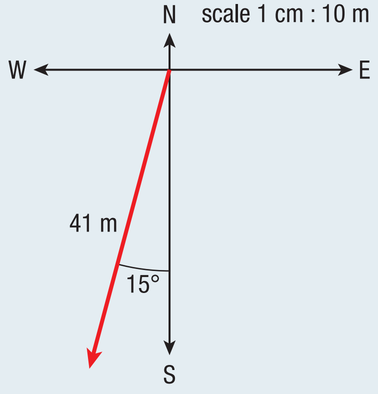

Figure 4 Scale diagram representing the displacement 41 m [S 15° W]

Practice

1. Choose a suitable scale to represent the vectors $\Delta\vec{d}_1 = 350$ m [E] and $\Delta\vec{d}_2 = 410$ m [E 35° N]. Use the scale to determine the lengths of the vectors representing $\Delta\vec{d}_1$ and $\Delta\vec{d}_2$. T/I
   [ans: 1 cm : 50 m, giving 7.0 cm and 8.2 cm, or 1 cm : 100 m, giving 3.5 cm and 4.1 cm]
2. Represent the vectors in Question 1 on a scale diagram using your chosen scale. T/I C

Now that you have learned how to draw two-dimensional displacement vectors using scale diagrams, we will apply this skill to adding displacement vectors in Tutorial 2.

Tutorial 2 Adding Displacement Vectors in Two Dimensions Using Scale Diagrams

In the following Sample Problems, we will analyze three different scenarios involving displacement vectors in two dimensions. In Sample Problem 1, we will add two displacement vectors that are perpendicular to each other. In Sample Problem 2, one of the vectors to be added is pointing due north, and the other is pointing at an angle to this direction. In Sample Problem 3, we will add two vectors that do not point due north, south, east, or west.

Sample Problem 1: Adding Two Perpendicular Vectors

A cyclist rides her bicycle 50 m due east, and then turns a corner and rides 75 m due north. What is her total displacement?

Given: $\Delta\vec{d}_1 = 50\text{ m [E]}$; $\Delta\vec{d}_2 = 75\text{ m [N]}$

Required: $\Delta\vec{d}_T$

Analysis: $\Delta\vec{d}_T = \Delta\vec{d}_1 + \Delta\vec{d}_2$

Solution: $\Delta\vec{d}_T = \Delta\vec{d}_1 + \Delta\vec{d}_2$

$$\Delta\vec{d}_T = 50\text{ m [E]} + 75\text{ m [N]}$$

We have two perpendicular vectors that we need to add together. To add these vectors by scale diagram, we need to determine a reasonable scale for our diagram, such as 1 cm : 10 m. We can then solve the problem in four steps: draw the first vector, draw the second vector, draw the resultant vector, and determine the resultant vector's magnitude and direction.

Step 1. Draw the first vector.

Before we begin drawing our diagram, we will first draw a Cartesian coordinate system (**Figure 5**). Recall that the point where the *x*-axis and the *y*-axis of a Cartesian coordinate system cross is known as the origin. In all of our scale diagrams, the first vector will be drawn so that the tail of the vector starts at the origin. The first displacement is 50 m, or 5 × 10 m, so applying the chosen scale of 1 cm : 10 m, we draw this displacement as a 5.0 cm long vector pointing due east, starting at the origin.

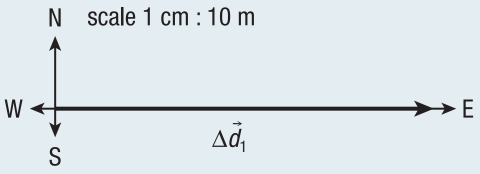

Figure 5 Vector $\Delta\vec{d}_1$, drawn to scale

Step 2. Join the second vector to the first vector tip to tail.

Figure 6 shows the second displacement vector drawn to scale represented as a vector of length 7.5 cm. Notice that the tail of this vector has been joined to the tip of the first vector. When vectors are being added, they must always be joined tip to tail.

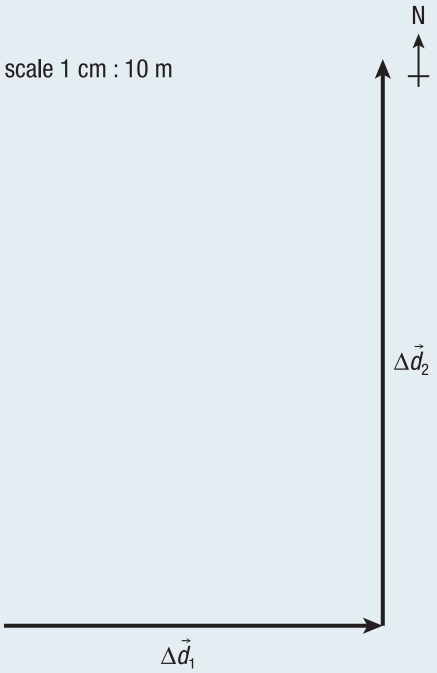

Figure 6 Add vector $\Delta\vec{d}_2$ to the scale diagram.

Step 3. Draw the resultant vector.

Figure 7 shows the resultant vector drawn from the tail of the first vector to the tip of the second vector. Resultant vectors are always drawn from the starting point in the diagram (the origin in our example) to the ending point. This diagram also indicates the angle θ (the Greek symbol theta) that the resultant vector makes with the horizontal.

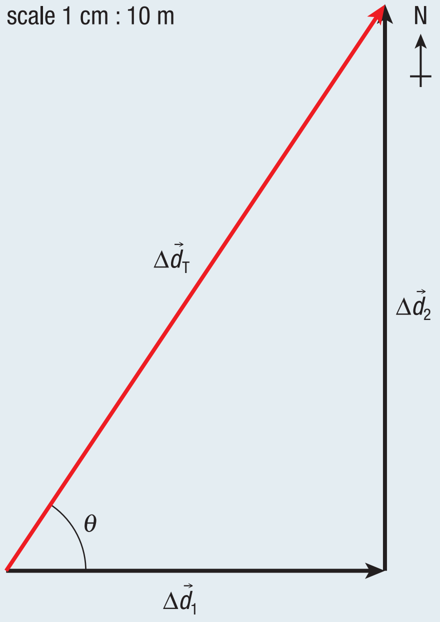

Figure 7 Draw the resultant vector.

To complete this problem, it is necessary to measure the length of the resultant vector $\Delta\vec{d}_T$ with a ruler and convert this measurement to the actual distance using the scale of the diagram. We must also measure the interior angle θ.

Step 4. Determine the magnitude and direction of the resultant vector.

As you can see from **Figure 8**, the resultant vector has length 9.0 cm. Using the scale, this vector represents a displacement of $9.0 \times (10\text{ m}) = 90$ m. Using a protractor, the interior angle is measured to be 56° from the horizontal or [E] direction. This gives a final displacement of $\Delta\vec{d}_T = 90$ m [E 56° N].

Statement: The cyclist's total displacement is 90 m [E 56° N].

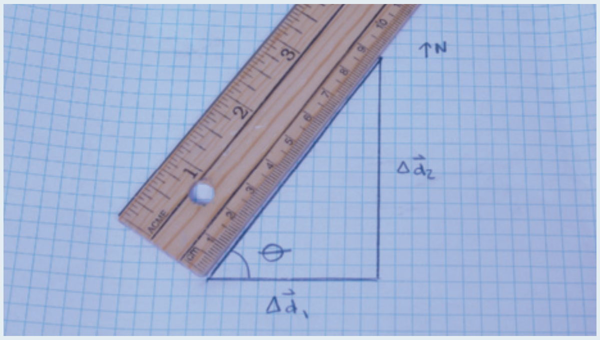

Figure 8 Using a ruler to measure the length of the resultant vector

In the next Sample Problem we will determine the total displacement of a sailboat when the direction of one of its displacements is not due north, south, east, or west.

Sample Problem 2: One Vector Is at an Angle

While in a race, a sailboat travels a displacement of 40 m [N]. The boat then changes direction and travels a displacement of 60 m [S 30° W]. What is the boat's total displacement?

Given: $\Delta\vec{d}_1 = 40\text{ m }[\text{N}]$; $\Delta\vec{d}_2 = 60$ m [S 30° W]

Required: $\Delta\vec{d}_T$

Analysis: $\Delta\vec{d}_T = \Delta\vec{d}_1 + \Delta\vec{d}_2$

Solution: $\Delta\vec{d}_T = \Delta\vec{d}_1 + \Delta\vec{d}_2$

$\Delta\vec{d}_T = 40\text{ m }[\text{N}] + 60$ m [S 30° W]

At this stage, the solution looks very similar to that shown in Sample Problem 1. The scale of 1 cm : 10 m used in Sample Problem 1 can be used again here. Now we must join the two vectors tip to tail using the steps shown in Sample Problem 1.

Figure 9 shows the first displacement drawn as a vector 4.0 cm in length pointing due north. The second displacement is drawn as a vector 6.0 cm in length and is joined to the first vector tip to tail. We use a protractor to make sure the second vector points 30° west of south (not south of west!). The resultant vector is again drawn from the starting point of motion to the ending point. The resultant vector is measured using a ruler, and the displacement is calculated using our chosen scale. Notice that the displacement is in the southwest quadrant.

It is necessary to measure the angle θ with the horizontal to determine the final direction. In this case, we measure this angle from the negative horizontal or west direction, below the *x*-axis. The total displacement can be described as $\Delta\vec{d}_T = 32$ m [W 22° S].

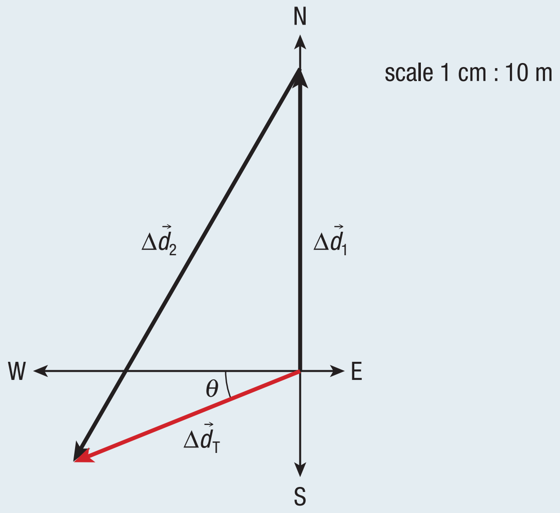

Figure 9 Adding the displacement vectors, tip to tail

Statement: The boat's total displacement is 32 m [W 22° S].

The most general vector addition problem is a situation in which neither displacement is pointing in the direction north, south, east, or west. The methods that we have used in Sample Problems 1 and 2 will also work in Sample Problem 3.

Sample Problem 3: Adding Two Non-perpendicular Vectors

A squash ball undergoes a displacement of 6.2 m [W 25° S] as it approaches a wall. It bounces off the wall and experiences a displacement of 4.8 m [W 25° N]. The whole motion takes 3.7 s. Determine the squash ball's total displacement and average velocity.

Given: $\Delta\vec{d}_1 = 6.2\text{ m [W 25° S]}$; $\Delta\vec{d}_2 = 4.8\text{ m [W 25° N]}$; $\Delta t = 3.7\text{ s}$

Required: $\Delta\vec{d}_\text{T}$; $\vec{v}_\text{av}$

Analysis: $\Delta\vec{d}_\text{T} = \Delta\vec{d}_1 + \Delta\vec{d}_2$

Solution: $\Delta\vec{d}_\text{T} = \Delta\vec{d}_1 + \Delta\vec{d}_2$

$$\Delta\vec{d}_\text{T} = 6.2\text{ m [W 25° S]} + 4.8\text{ m [W 25° N]}$$

To add these vectors, we will use a scale of 1 cm : 1 m. From **Figure 10,** we can determine the final displacement to be $\Delta\vec{d}_\text{T} = 10\text{ m [W 3° S]}$.

Recall from Chapter 1 that average velocity $\vec{v}_\text{av}$ can be calculated algebraically as

$$\vec{v}_\text{av} = \frac{\Delta\vec{d}}{\Delta t}$$

We can use the value $\Delta\vec{d}_\text{T} = 10\text{ m [W 3° S]}$ for the total displacement to calculate the average velocity.

$$\begin{aligned}\vec{v}_\text{av} &= \frac{\Delta\vec{d}}{\Delta t}\\ &= \frac{10\text{ m [W 3° S]}}{3.7\text{ s}}\\ \vec{v}_\text{av} &= 2.7\text{ m/s [W 3° S]}\end{aligned}$$

Statement: The squash ball's total displacement is 10 m [W 3° S] and its average velocity is 2.7 m/s [W 3° S].

Notice that both vectors are in the same direction. This is because average velocity is calculated by dividing displacement (a vector) by time (a scalar with a positive value). Dividing a vector by a positive scalar does not affect the direction of the resultant vector (average velocity).

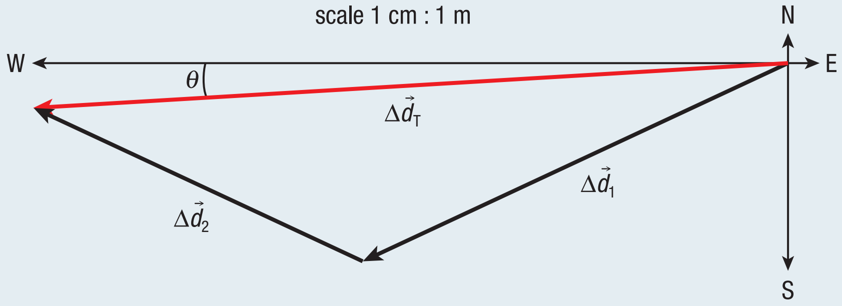

Figure 10 Adding the displacement vectors

Practice

1. Use a scale diagram to determine the sum of each pair of displacements. T/I C
   (a) $\Delta\vec{d}_1 = 72\text{ cm [W]}$, $\Delta\vec{d}_2 = 46\text{ cm [N]}$ [ans: 85 cm [W 33° N]]
   (b) $\Delta\vec{d}_1 = 65.3\text{ m [E 42° N]}$, $\Delta\vec{d}_2 = 94.8\text{ m [S]}$ [ans: 70.5 m [E 46° S]]
2. A cyclist travels 450 m [W 35° S] and then rounds a corner and travels 630 m [W 60° N]. T/I
   (a) What is the cyclist's total displacement? [ans: 740 m [W 23° N]]
   (b) If the whole motion takes 77 s, what is the cyclist's average velocity? [ans: 9.6 m/s [W 23° N]]

2.1 Summary

- Objects can move in two dimensions, such as in a horizontal plane and a vertical plane.
- The compass rose can be used to express directions in a horizontal plane, such as [N 40° W].
- To determine total displacement in two dimensions, displacement vectors can be added together using a scale diagram. To add two or more vectors together, join them tip to tail and draw the resultant vector from the tail of the first vector to the tip of the last vector.

2.1 Questions

1. Draw a Cartesian coordinate system on a sheet of paper. On this Cartesian coordinate system, draw each vector to scale, starting at the origin. T/I C
   (a) $\Delta\vec{d} = 8.0$ cm [S 15° E]
   (b) $\Delta\vec{d} = 5.7$ cm [N 35° W]
   (c) $\Delta\vec{d} = 4.2$ cm [N 18° E]
2. How could you express the direction of each vector listed in Question 1 differently so that it still describes the same vector? C
3. The scale diagram shown in **Figure 11** represents two vectors. T/I

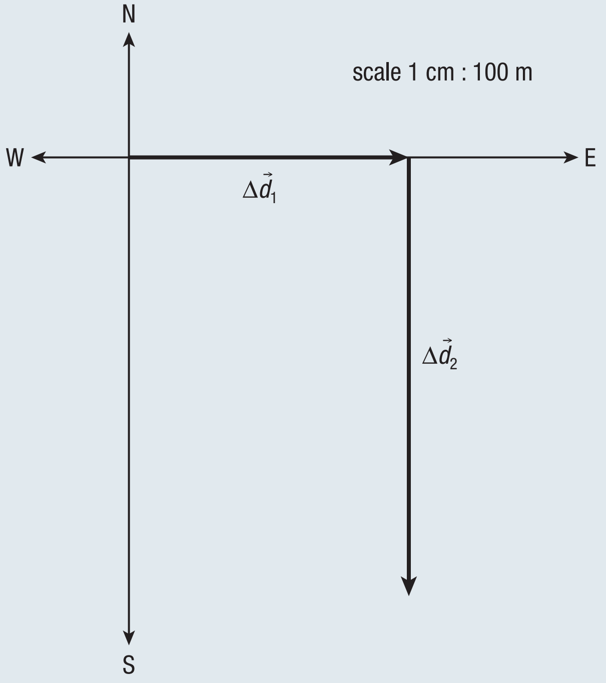

Figure 11

   (a) Use the given scale to determine the actual vectors.
   (b) Copy the scale diagram and complete it to determine the resultant vector when the two vectors are added.
4. A taxi drives 300.0 m south and then turns and drives 180.0 m east. What is the total displacement of the taxi? T/I
5. What is the total displacement of two trips, one of 10.0 km [N] and the other of 24 km [E]? T/I
6. If you added the two displacements in Question 5 in the opposite order, would you get the same answer? Explain. K/U
7. A horse runs 15 m [N 23° E] and then 32 m [S 35° E]. What is the total displacement of the horse? T/I
8. A car travels 28 m [E 35° S] and then turns and travels 45 m [S]. The whole motion takes 6.9 s. T/I
   (a) What is the car's average velocity?
   (b) What is the car's average speed?
9. An aircraft experiences a displacement of 100.0 km [N 30° E] due to its engines. The aircraft also experiences a displacement of 50.0 km [W] due to the wind. T/I
   (a) What is the total displacement of the aircraft?
   (b) If it takes 10.0 min for the motion to occur, what is the average velocity, in kilometres per hour, of the aircraft during this motion?

2.2 Motion in Two Dimensions— An Algebraic Approach

In Section 2.1 you learned how to solve motion problems in two dimensions by using vector scale diagrams. This method has some limitations. First, the method is not very precise. Second, scale diagrams can become very cumbersome when you need to add more than two vectors. The map in **Figure 1** shows several different legs of a trip. Each leg represents an individual displacement. Without the map and the scale, adding these displacements by scale diagram would be quite challenging. In many situations an algebraic approach is a better way to add vectors. To use this method, we will revisit some of the mathematics from Grade 10—the Pythagorean theorem and trigonometry.

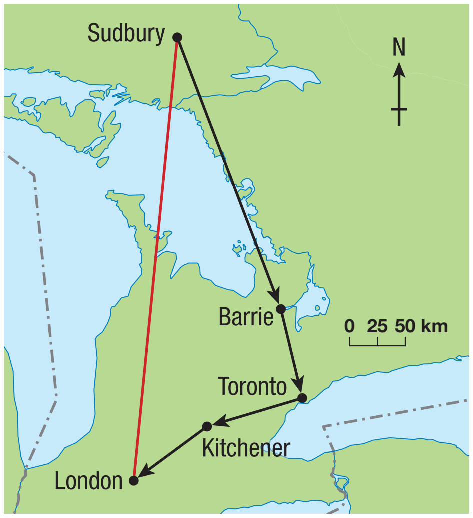

Figure 1 How would you determine the total displacement from Sudbury to London in this problem?

CAREER LINK

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Adding Displacements in Two Dimensions

GPS technology, which surveyors use to precisely locate positions, depends on computing the resultant vector when displacement vectors are added together. Tutorials 1 to 3 introduce the algebraic method of adding vectors. If two displacements are perpendicular to each other, we can add them relatively easily. Adding non-perpendicular displacements algebraically involves breaking them down into perpendicular parts.

Tutorial 1 Adding Two Perpendicular Displacements Using Algebra

In this Tutorial, we will use an algebraic approach to add two perpendicular displacements.

Sample Problem 1: Adding Two Perpendicular Vectors

A jogger runs 200.0 m [E], turns at an intersection, and continues for an additional displacement of 300.0 m [N]. What is the jogger's total displacement?

Given: $\Delta\vec{d}_1 = 200.0\text{ m [E]}$; $\Delta\vec{d}_2 = 300.0\text{ m [N]}$

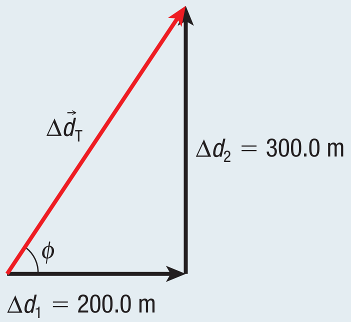
Required: $\Delta\vec{d}_T$

Analysis: $\Delta\vec{d}_T = \Delta\vec{d}_1 + \Delta\vec{d}_2$

Solution: $\Delta\vec{d}_T = \Delta\vec{d}_1 + \Delta\vec{d}_2$

$$\Delta\vec{d}_T = 200.0\text{ m [E]} + 300.0\text{ m [N]}$$

At this point, we can draw a diagram showing these two vectors joined tip to tail (**Figure 2**). Notice that this is only a sketch—*it is not a scale diagram*.



$\Delta\vec{d}_T$
$\Delta d_2 = 300.0$ m
ϕ
$\Delta d_1 = 200.0$ m

Figure 2 The two given displacement vectors, joined tip to tail

Notice that vector arrows are not shown above Δd_1 and Δd_2 in Figure 2. This is because only the magnitudes of these two displacements are shown in the diagram. The directions are represented by the direction of each vector as drawn in the diagram. The Greek symbol ϕ (phi) is used to represent the angle of the resultant vector with respect to the *x*-axis.

Now we need to determine the magnitude and direction of $\Delta\vec{d}_T$. Since this is a right triangle, we can use the Pythagorean theorem to solve for the magnitude of this vector:

$$\begin{aligned}
\Delta d_T^2 &= \Delta d_1^2 + \Delta d_2^2 \\
\Delta d_T &= \sqrt{\Delta d_1^2 + \Delta d_2^2} \\
&= \sqrt{(200.0\text{ m})^2 + (300.0\text{ m})^2} \\
\Delta d_T &= 360.6\text{ m}
\end{aligned}$$

To determine the direction, we need to calculate the magnitude of the angle using the tangent ratio:

$$\begin{aligned}
\tan\phi &= \frac{\Delta d_2}{\Delta d_1} \\
\tan\phi &= \frac{300.0\text{ m}}{200.0\text{ m}} \\
\tan\phi &= 1.5 \\
\phi &= \tan^{-1}(1.5) \\
\phi &= 56^\circ
\end{aligned}$$

Stating the magnitude and direction gives $\Delta\vec{d}_T = 360.6$ m [E 56° N].

Statement: The jogger's total displacement is 360.6 m [E 56° N].

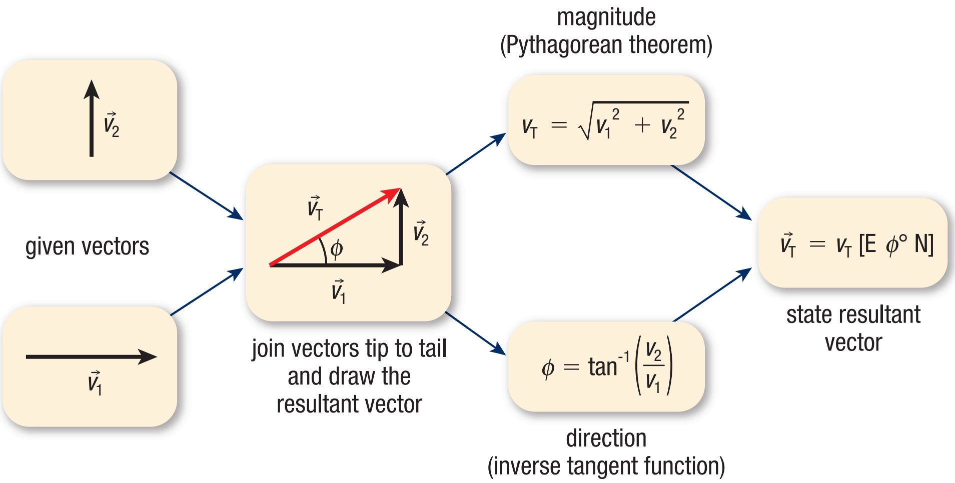
Practice

1. Add the following perpendicular displacement vectors algebraically: T/I

   $\Delta\vec{d}_1 = 27$ m [W], $\Delta\vec{d}_2 = 35$ m [S] [ans: 44 m [W 52° S]]

2. What is the vector sum of the displacements $\Delta\vec{d}_1 = 13.2$ m [S] and $\Delta\vec{d}_2 = 17.8$ m [E]? T/I [ans: 22.2 m [E 37° S]]

The graphic organizer in **Figure 3** summarizes the method for adding two perpendicular vectors algebraically.



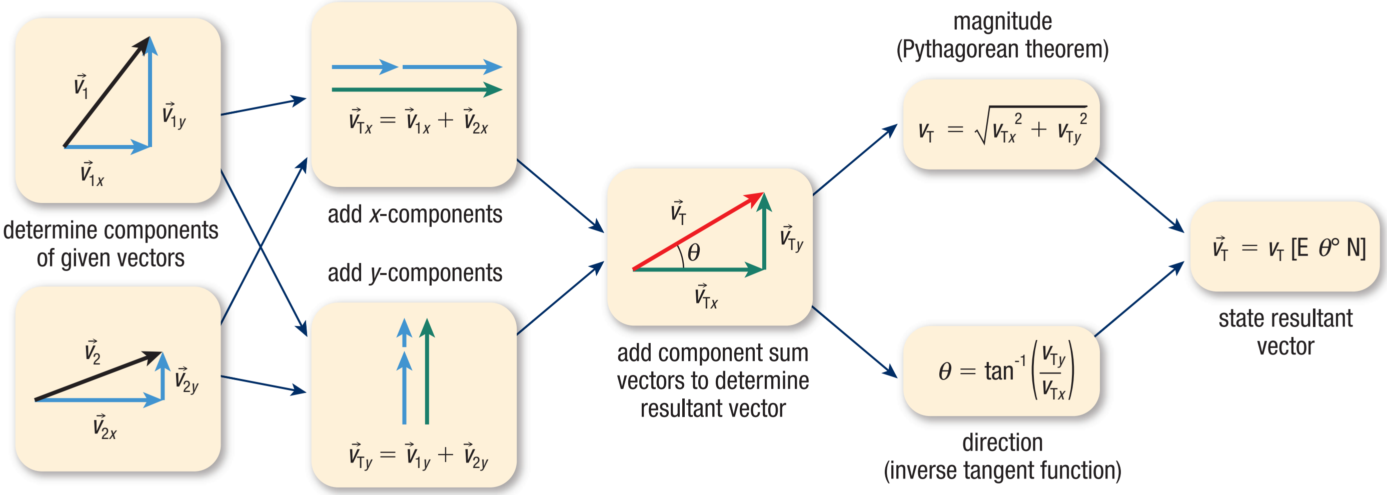
magnitude
(Pythagorean theorem)
$\vec{v}_2$
$v_T = \sqrt{v_1^2 + v_2^2}$
$\vec{v}_T$
$\vec{v}_2$
ϕ
$\vec{v}_1$
given vectors
$\vec{v}_T = v_T$ [E ϕ° N]
state resultant vector
$\vec{v}_1$
join vectors tip to tail and draw the resultant vector
$\phi = \tan^{-1}\left(\frac{v_2}{v_1}\right)$
direction
(inverse tangent function)

Figure 3 Adding two perpendicular vectors algebraically

Sample Problem 1 in Tutorial 1 is a very important example. Our goal from this point on, when solving more complex problems, is to turn every vector addition problem into a problem similar to Sample Problem 1. That is, we will turn every problem into a situation where we are adding two perpendicular vectors. The method for doing this is shown in **Figure 4**.

Figure 4 builds on the methods introduced in Figure 3. In Figure 4, each given vector is broken down into *x* (horizontal) and *y* (vertical) **component vectors**. All of the *x*-component vectors in this example have the same direction, and we can add them together (just as we did in Chapter 1) to get an overall *x*-vector. Similarly, all of the *y*-component vectors are added together to get an overall *y*-vector. These two overall vectors are perpendicular to each other and can be added together as we did in Sample Problem 1 of Tutorial 1. This will be our procedure in Tutorial 2 and Tutorial 3, but how do we take a vector and break it down into two perpendicular components? We will use trigonometry.

component vectors vectors which when added together give the original vector from which they were derived; one component is parallel to the *x*-axis and the other is parallel to the *y*-axis



$\vec{v}_1$
$\vec{v}_{1y}$
$\vec{v}_{1x}$
determine components of given vectors
$\vec{v}_2$
$\vec{v}_{2y}$
$\vec{v}_{2x}$
$\vec{v}_{Tx} = \vec{v}_{1x} + \vec{v}_{2x}$
add *x*-components
add *y*-components
$\vec{v}_{Ty} = \vec{v}_{1y} + \vec{v}_{2y}$
$\vec{v}_T$
θ
$\vec{v}_{Ty}$
$\vec{v}_{Tx}$
add component sum vectors to determine resultant vector
magnitude (Pythagorean theorem)
$v_T = \sqrt{v_{Tx}^{\ 2} + v_{Ty}^{\ 2}}$
$\theta = \tan^{-1}\left(\frac{v_{Ty}}{v_{Tx}}\right)$
direction (inverse tangent function)
$\vec{v}_T = v_T\ [\text{E } \theta^\circ \text{ N}]$
state resultant vector

Figure 4 Adding two non-perpendicular vectors algebraically

Tutorial **2** Breaking Down Vectors into Two Perpendicular Components

In this Tutorial, we will go through the process required to break down a vector into perpendicular components.

Sample Problem 1: Breaking Down Vectors into Component Vectors

Break the displacement vector 30.0 m [E 25° N] down into two perpendicular component vectors.

Given: $\Delta\vec{d}_T = 30.0\ \text{m}\ \ [\text{E } 25^\circ \text{ N}]$

Required: $\Delta\vec{d}_x; \Delta\vec{d}_y$

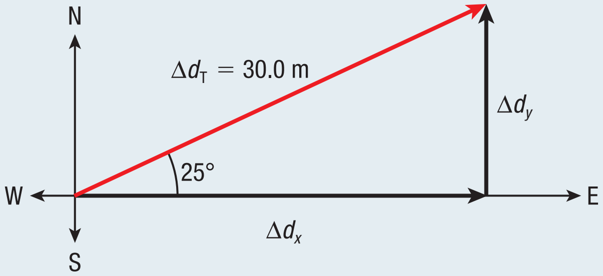
Analysis: $\Delta\vec{d}_T = \Delta\vec{d}_x + \Delta\vec{d}_y$

In this case, we need to work backwards from $\Delta\vec{d}_T$ to determine the horizontal and vertical component vectors.

Solution: $\Delta\vec{d}_T = \Delta\vec{d}_x + \Delta\vec{d}_y$

$$\Delta\vec{d}_T = 30.0\ \text{m}\ [\text{E } 25^\circ \text{ N}] \ = \Delta\vec{d}_x + \Delta\vec{d}_y$$

In **Figure 5** the two component vectors $\Delta\vec{d}_x$ and $\Delta\vec{d}_y$ are drawn and joined tip to tail. These two vectors are joined such that the *x*-component vector ($\Delta\vec{d}_x$) is along the *x*-axis. As we will see, this is a good habit to develop because it will help to minimize your chances of making an error when solving problems involving vector components.



N
W
E
S
$\Delta d_T = 30.0$ m
Δd_y
25°
Δd_x

Figure 5 A displacement vector in the northeast quadrant of a Cartesian coordinate system

The direction of each component vector is clear from the diagram. $\Delta\vec{d}_x$ points due east, and $\Delta\vec{d}_y$ points due north. To determine the magnitude of each vector, you need to recall some trigonometry from Grade 10 math, specifically the sine and cosine functions.

Recall that

$$\sin\theta = \frac{\text{opposite}}{\text{hypotenuse}}$$

In this case,

$$\sin\theta = \frac{\Delta d_y}{\Delta d_T}$$

Solving for Δd_y, we get

$$\begin{aligned}\Delta d_y &= \Delta d_T \sin\theta \\ &= (30.0\ \text{m})(\sin 25°) \\ \Delta d_y &= 12.68\ \text{m (two extra digits carried)}\end{aligned}$$

The y-component of this vector has magnitude 12.68 m (and direction [N]).

To determine the x-component of the given vector, we will use a similar method. In this case, however, we will use the cosine function. Recall that

$$\cos\theta = \frac{\text{adjacent}}{\text{hypotenuse}}$$

In this case,

$$\cos\theta = \frac{\Delta d_x}{\Delta d_T}$$

Solving for Δd_x, we get

$$\begin{aligned}\Delta d_x &= \Delta d_T \cos\theta \\ &= (30.0\ \text{m})(\cos 25°) \\ \Delta d_x &= 27.19\ \text{m (two extra digits carried)}\end{aligned}$$

The x-component of this vector has magnitude 27.19 m (and direction [E]).

Adding the two component vectors such that $\Delta\vec{d}_x = 27.19$ m [E] and $\Delta\vec{d}_y = 12.68$ m [N], we get a resultant vector equal to 30.0 m [E 25° N], which was the original given vector.

Statement: The vector 30.0 m [E 25° N] has a horizontal or x-component of 27.2 m [E] and a vertical or y-component of 12.7 m [N].

Practice

1. Determine the magnitude and direction of the x-component and y-component vectors for the displacement vector $\Delta\vec{d}_T = 15\ \text{m}\ [\text{W } 35^\circ \text{ N}]$. T/I [ans: $\Delta\vec{d}_x = 12$ m [W], $\Delta\vec{d}_y = 8.6$ m [N]]
2. Add the two component vectors from Sample Problem 1 algebraically to verify that they equal the given vector. T/I

Tutorial 3 Adding Displacement Vectors by Components

In each of the following Sample Problems we will add a pair of two-dimensional vectors together by the component method. Notice that when you draw the initial diagram in a component-method solution, you should draw all vectors, starting at the origin, on a Cartesian coordinate system. In this diagram the vectors will *not* be joined tip to tail, as we did in Section 2.1. Also notice that all x-components will be drawn along the x-axis. This will ensure that all x-components contain a cosine term and all y-components contain a sine term, minimizing your chance of making an error.

Sample Problem 1: One Vector Has a Direction Due North, South, East, or West

A cat walks 20.0 m [W] and then turns and walks a further 10.0 m [S 40° E]. What is the cat's total displacement?

Given: $\Delta\vec{d}_1 = 20.0\ \text{m}\ [\text{W}]$; $\Delta\vec{d}_2 = 10.0\ \text{m}\ [\text{S } 40^\circ \text{ E}]$

Required: $\Delta\vec{d}_T$

Analysis: $\Delta\vec{d}_T = \Delta\vec{d}_1 + \Delta\vec{d}_2$

Solution: $\Delta\vec{d}_T = \Delta\vec{d}_1 + \Delta\vec{d}_2$

$$\Delta\vec{d}_T = 20.0\ \text{m}\ [\text{W}] + 10.0\ \text{m}\ [\text{S } 40^\circ \text{ E}]$$

Figure 6 on the next page shows the given displacement vectors drawn on a Cartesian coordinate system, both starting at the origin. Notice that vector $\Delta\vec{d}_1$ has only one component, specifically an x-component. Since this vector points due west, it does not have a y-component. On the other hand, vector $\Delta\vec{d}_2$ has two components. Notice that $\Delta\vec{d}_2$ is broken down so that the x-component lies on the x-axis.

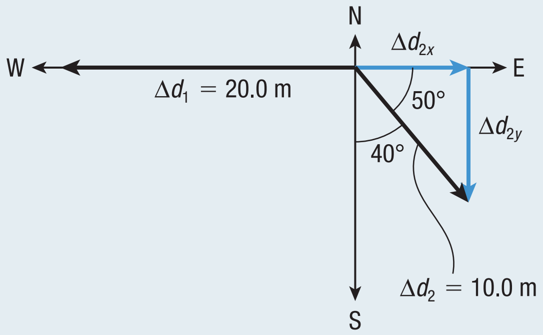


Figure 6 Start both vectors at the origin. (Diagram is not to scale.)

We begin by finding the vector sum of the x-components. In this case the vector sum of the x-components is represented by $\Delta\vec{d}_{Tx}$.

$$\Delta\vec{d}_{Tx} = \Delta\vec{d}_1 + \Delta\vec{d}_{2x}$$

From the diagram it is clear that $\Delta\vec{d}_1$ points due west, whereas $\Delta\vec{d}_{2x}$ points due east. So,

$$\begin{aligned}\Delta\vec{d}_{Tx} &= \Delta d_1\,[\text{W}] + \Delta d_{2x}\,[\text{E}]\\ &= \Delta d_1\,[\text{W}] + \Delta d_2 \cos 50°\,[\text{E}]\\ &= 20.0\text{ m}\,[\text{W}] + (10.0\text{ m})(\cos 50°)[\text{E}]\\ \Delta\vec{d}_{Tx} &= 20.0\text{ m}\,[\text{W}] + 6.428\text{ m}\,[\text{E}]\end{aligned}$$

We can change the direction of the smaller vector by placing a negative sign in front of the magnitude. This gives both vectors the same direction.

$$\begin{aligned}\Delta\vec{d}_{Tx} &= 20.0\text{ m}\,[\text{W}] - 6.428\text{ m}\,[\text{W}]\\ \Delta\vec{d}_{Tx} &= 13.572\text{ m}\,[\text{W}]\text{ (two extra digits carried)}\end{aligned}$$

The overall vector sum of all x-components is 13.572 m [W]. Notice that two extra significant digits have been carried here. This is to minimize rounding error. Always carry one or two extra significant digits when a calculated value will be used in subsequent calculations. You should round down to the correct number of significant digits once you have calculated the final answer to the question.

We can solve for the vector sum of all y-components in a very similar way. In this case, there is only one y-component. This is the vector $\Delta\vec{d}_{2y}$.

$$\begin{aligned}\Delta\vec{d}_{Ty} &= 0 + \Delta\vec{d}_{2y}\\ &= \Delta d_2 \sin 50°\,[\text{S}]\\ &= (10.0\text{ m})(\sin 50°)[\text{S}]\\ \Delta\vec{d}_{Ty} &= 7.660\text{ m}\,[\text{S}]\end{aligned}$$

Notice that we have converted this problem into one involving two perpendicular vectors, namely $\Delta\vec{d}_{Tx}$ and $\Delta\vec{d}_{Ty}$. We can now join these two vectors tip to tail, as shown in **Figure 7**. We will use the Pythagorean theorem to determine the magnitude and the tangent function to determine the direction of the total displacement.

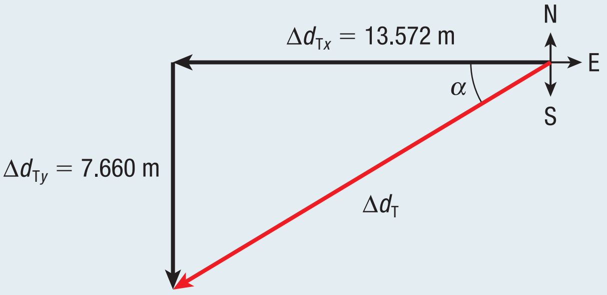

N
$\Delta d_{Tx} = 13.572\text{ m}$
E
α
S
$\Delta d_{Ty} = 7.660\text{ m}$
Δd_T

Figure 7 Use the total components to determine the total displacement.

$$\begin{aligned}\Delta d_T^2 &= (\Delta d_{Tx})^2 + (\Delta d_{Ty})^2\\ \Delta d_T &= \sqrt{(\Delta d_{Tx})^2 + (\Delta d_{Ty})^2}\\ &= \sqrt{(13.572\text{ m})^2 + (7.660\text{ m})^2}\\ \Delta d_T &= 15.6\text{ m}\end{aligned}$$

To determine the angle α (alpha) that $\Delta\vec{d}_T$ makes with the x-axis, we can use the tangent function.

$$\begin{aligned}\tan\alpha &= \frac{\Delta d_{Ty}}{\Delta d_{Tx}}\\ \tan\alpha &= \frac{7.660\text{ m}}{13.572\text{ m}}\\ \alpha &= 29°\end{aligned}$$

Statement: The total displacement of the cat is 15.6 m [W 29° S].

Sample Problem 2: Neither Vector Has a Direction Due North, South, East, or West

A hockey puck travels a displacement of 4.2 m [S 38° W]. It is then struck by a hockey player's stick and undergoes a displacement of 2.7 m [E 25° N]. What is the puck's total displacement?

Given: $\Delta\vec{d}_1 = 4.2\text{ m}\,[\text{S }38°\text{ W}]$; $\Delta\vec{d}_2 = 2.7\text{ m}\,[\text{E }25°\text{ N}]$

Required: $\Delta\vec{d}_T$

Analysis: $\Delta\vec{d}_T = \Delta\vec{d}_1 + \Delta\vec{d}_2$

Solution: $\Delta\vec{d}_T = \Delta\vec{d}_1 + \Delta\vec{d}_2$

$$\Delta\vec{d}_T = 4.2\text{ m}\,[\text{S }38°\text{ W}] + 2.7\text{ m}\,[\text{E }25°\text{ N}]$$

Figure 8 shows the two displacements to be added. Both displacements start at the origin—they are not drawn tip to tail (as we did when adding vectors by scale diagram).

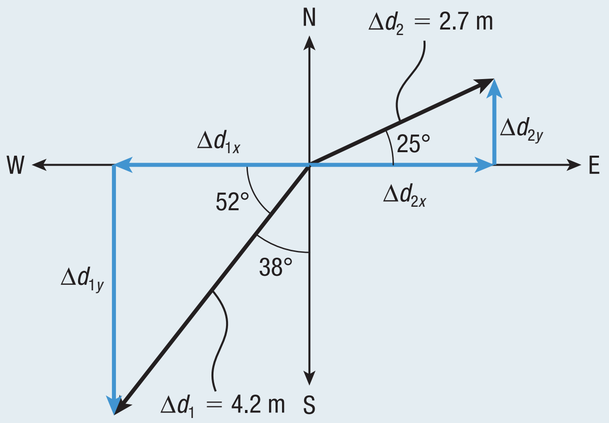


Figure 8 Draw both given vectors starting at the origin.

We begin by determining the total *x*-component and *y*-component of $\Delta\vec{d}_T$. For the *x*-component,

$$
\begin{aligned}
\vec{d}_{Tx} &= \Delta\vec{d}_{1x} + \Delta\vec{d}_{2x} \\
&= \Delta d_1 \cos 52^\circ\,[W] + \Delta d_2 \cos 25^\circ\,[E] \\
&= (4.2\text{ m})(\cos 52^\circ)\,[W] + (2.7\text{ m})(\cos 25^\circ)\,[E] \\
&= 2.59\text{ m}\,[W] + 2.45\text{ m}\,[E] \\
&= 2.59\text{ m}\,[W] - 2.45\text{ m}\,[W] \\
\vec{d}_{Tx} &= 0.14\text{ m}\,[W]
\end{aligned}
$$

For the *y*-component,

$$
\begin{aligned}
\vec{d}_{Ty} &= \Delta\vec{d}_{1y} + \Delta\vec{d}_{2y} \\
&= \Delta d_1 \sin 52^\circ\,[W] + \Delta d_2 \sin 25^\circ\,[E] \\
&= (4.2\text{ m})(\sin 52^\circ)\,[S] + (2.7\text{ m})(\sin 25^\circ)\,[N] \\
&= 3.31\text{ m}\,[S] + 1.14\text{ m}\,[N] \\
&= 3.31\text{ m}\,[S] - 1.14\text{ m}\,[S] \\
\Delta\vec{d}_{Ty} &= 2.17\text{ m}\,[S]
\end{aligned}
$$

We now use the total *x*-component and *y*-component to determine the magnitude of $\Delta\vec{d}_T$ (**Figure 9**).

$$
\begin{aligned}
\Delta d_T^{\,2} &= d_{Tx}^{\,2} + d_{Ty}^{\,2} \\
\Delta d_T &= \sqrt{d_{Tx}^{\,2} + d_{Ty}^{\,2}} \\
&= \sqrt{(0.14\text{ m})^2 + (2.17\text{ m})^2} \\
\Delta d_T &= 2.2\text{ m}
\end{aligned}
$$

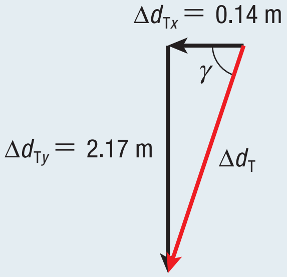


Figure 9 Determining the total displacement

We use the tangent function to determine the angle γ (gamma) that $\Delta\vec{d}_T$ makes with the *x*-axis.

$$
\begin{aligned}
\tan\gamma &= \frac{d_{Ty}}{d_{Tx}} \\
\tan\gamma &= \frac{2.17\text{ m}}{0.14\text{ m}} \\
\gamma &= 86^\circ
\end{aligned}
$$

Statement: The puck's total displacement is 2.2 m [W 86° S].

Practice

1. An ant travels 2.78 cm [W] and then turns and travels 6.25 cm [S 40° E]. What is the ant's total displacement? T/I [ans: 4.94 cm [E 76° S]]
2. A paper airplane flies 2.64 m [W 26° N] and then is caught by the wind, which causes it to travel 3.21 m [S 12° E]. What is the paper airplane's total displacement? T/I [ans: 2.62 m [W 49° S]]

Adding Velocities in Two Dimensions

What does it mean, physically, to add two velocity vectors? Imagine driving a boat across a still lake. If you know your velocity and the width of the lake, you can easily determine how long it will take you to reach the other side. If instead you are crossing a river (**Figure 10**), you have two velocities to consider: the velocity due to your boat's engine and the velocity at which the river is flowing. Does the flow of the river change your crossing time? How far downstream will you be carried as you drive across? To answer questions like this, we will use the skills of algebraic vector addition that you have already learned in Tutorial 4.

Figure 10 Two motions are involved in crossing a river—yours and the river's.

Tutorial 4 River Crossing Problems

River crossing problems are a type of two-dimensional motion problem that involve perpendicular velocity vectors. The “river crossing problem” is often first introduced in terms of boats crossing rivers, but it may also involve aircraft flying through the air, and so on. These types of problems always involve two perpendicular motions that are independent of each other.

CASE 1: DETERMINING THE TIME IT TAKES FOR A RIVER CROSSING WITHOUT TAKING CURRENT INTO ACCOUNT

Sample Problem 1

Consider the river shown in **Figure 11**. A physics student has forgotten her lunch and needs to return home to retrieve it. To do so she hops into her motorboat and steers straight across the river at a constant velocity of 12 km/h [N]. If the river is 0.30 km across and has no current, how long will it take her to cross the river?

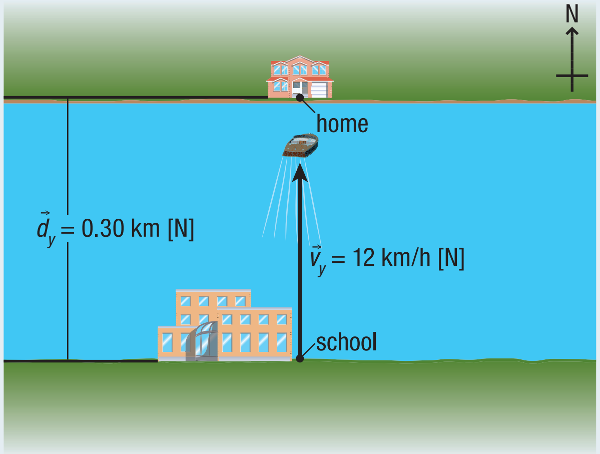


Figure 11 River crossing with no current

Let $\vec{v}_y$ represent the velocity caused by the boat’s motor.

Given: $\Delta\vec{d}_y = 0.30\text{ km [N]}$, $\vec{v}_y = 12\text{ km/h [N]}$

Required: Δt

Analysis: Since the boat is travelling at a constant velocity, we can solve this problem using the defining equation for average velocity. Since displacement and average velocity are in the same direction, we can simply divide one magnitude by the other when we rearrange this equation.

$$\begin{aligned}\vec{v}_y &= \frac{\Delta\vec{d}_y}{\Delta t}\\ \vec{v}_y(\Delta t) &= \Delta\vec{d}_y\\ \Delta t &= \frac{\Delta d_y}{v_y}\end{aligned}$$

Solution: $\Delta t = \dfrac{\Delta d_y}{v_y}$

$$\begin{aligned}&= \frac{0.30\ \cancel{\text{km}}}{12\ \dfrac{\cancel{\text{km}}}{\text{h}}}\\ \Delta t &= 0.025\text{ h}\end{aligned}$$

Statement: It will take the student 0.025 h or 1.5 min to cross the river.

CASE 2: DETERMINING THE DISTANCE TRAVELLED DOWNSTREAM DUE TO A RIVER CURRENT

Sample Problem 2

The river crossing problem in Sample Problem 1 is not very realistic because a river usually has a current. So we introduce a current here, in Sample Problem 2, and see how the current affects the trip across the river. **Figure 12** shows the same boat from Sample Problem 1 going at the same velocity. Let us now assume that the gate of a reservoir has been opened upstream, and the river water now flows with a velocity of 24 km/h [E]. This current has a significant effect on the motion of the boat. The boat is now pushed due north by its motor and due east by the river’s current. This causes the boat to experience two velocities at the same time, one due north and another due east. In Figure 12 these two velocity vectors are joined tip to tail to give a resultant velocity represented by $\vec{v}_T$. Notice that even though the student is steering the boat due north, the boat does not arrive at her home. Instead it lands some distance farther downstream.

(a) How long does it now take the boat to cross the river?

(b) How far downstream does the boat land?

(c) What is the boat’s resultant velocity $\vec{v}_T$?

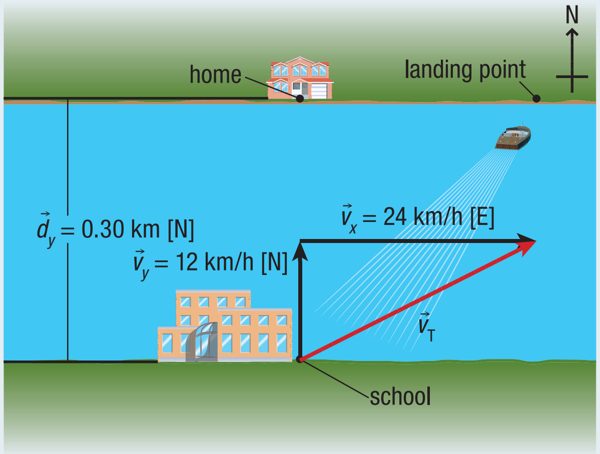

N
home
landing point
$\vec{d}_y = 0.30$ km [N]
$\vec{v}_y = 12$ km/h [N]
$\vec{v}_x = 24$ km/h [E]
$\vec{v}_T$
school

Figure 12 River crossing including a current

(a) **Given:** $\Delta\vec{d}_y = 0.30\text{ km [N]}$; $\vec{v}_y = 12\text{ km/h [N]}$;

$\vec{v}_x = 24\text{ km/h [E]}$

Required: Δt

First we will consider the motion of the boat moving across the river.

Analysis: $\vec{v}_y = \dfrac{\Delta\vec{d}_y}{\Delta t}$

$$\Delta t = \frac{\Delta d_y}{v_y}$$

Solution: $\Delta t = \dfrac{\Delta d_y}{v_y}$

$$= \frac{0.30\ \cancel{\text{km}}}{12\ \dfrac{\cancel{\text{km}}}{\text{h}}}$$

$$\Delta t = 0.025\text{ h}$$

Statement: The time it takes the boat to cross the river is still 0.025 h.

Surprisingly, the time it now takes to cross the river is precisely the same time as it took when there was no current in the river. It will still take 0.025 h. How can this be? Notice that in this Sample Problem, the current pushes the boat in a direction that is perpendicular to the direction in which the boat's motor pushed the boat. Thus, the current's velocity is perpendicular to the velocity vector caused by the boat's motor. Since the current velocity $\vec{v}_x$ does not have a component in a direction parallel to that of the velocity caused by the boat's motor, $\vec{v}_y$, it will not cause the velocity in the direction of $\vec{v}_y$ to increase or decrease.

Consider the hypothetical situation shown in **Figure 13**. This figure is almost identical to Figure 12, except that in this example the velocity due to the current $\vec{v}_c$ is not perpendicular to the velocity due to the boat's motor $\vec{v}_y$. In this case, the velocity due to the current can be broken down into perpendicular components, one moving downstream, $\vec{v}_{cx}$, and one moving across the river, $\vec{v}_{cy}$. $\vec{v}_{cy}$ is in the opposite direction to $\vec{v}_y$. This causes a reduction in the velocity of the boat across the river. If $\vec{v}_{cy}$ is greater than $\vec{v}_y$, the boat can never leave the dock. It is continuously washed back onto the shore near the school. In reality, this never happens. In real situations, the current flows parallel to the riverbanks.

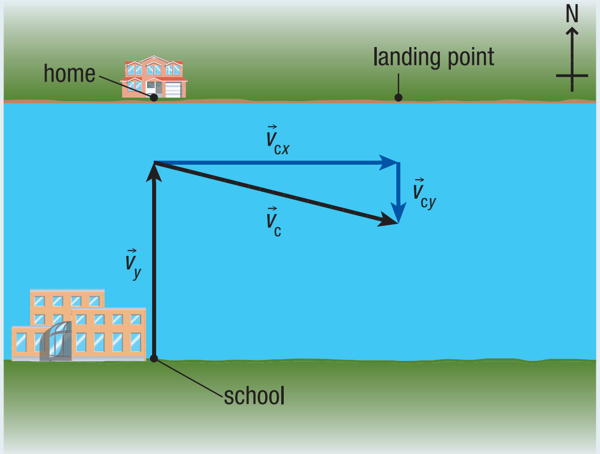


Figure 13 River crossing with an unrealistic current

(b) We now return to our Sample Problem described in Figure 12, where vector $\vec{v}_y$ is perpendicular to the vector $\vec{v}_x$. To calculate how far downstream the boat travels before it reaches the shore, we only need to consider velocities that are moving the boat downstream. In our example the only velocity moving the boat downstream is the current velocity, $\vec{v}_x$. So we can consider this to be a standard uniform velocity problem. Notice that the time that the motion downstream takes is identical to the time we calculated for the boat to move across the river in (a). In river crossing problems the time it takes to cross the river is the same as the time to move down the river. This is because the boat eventually reaches the opposite shore. We can presume that when the boat reaches the opposite shore, both the boat's motion across the river and its motion downstream will stop. As a result, in this example it takes the boat the same amount of time to cross the river as it does to travel downstream.

Given: $\vec{v}_x = 24\ \text{km/h [E]};\ \Delta t = 0.025\ \text{h}$

Required: $\Delta\vec{d}_x$

Analysis: $\vec{v}_x = \dfrac{\Delta\vec{d}_x}{\Delta t}$

$$\Delta\vec{d}_x = \vec{v}_x(\Delta t)$$

Solution:
$$\begin{aligned}\Delta\vec{d}_x &= \vec{v}_x(\Delta t)\\ &= (24\ \text{km/h [E]})(0.025\ \text{h})\\ \Delta\vec{d}_x &= 0.60\ \text{km [E]}\end{aligned}$$

Statement: As a result of the current, the boat will land 0.60 km east, or downstream, of the student's home.

(c) The velocity labelled as $\vec{v}_\text{T}$ in Figure 12 is often referred to as the resultant velocity. The resultant velocity is the vector sum of the velocity due to the boat's motor and the velocity due to the current. This is the velocity that you would see the boat travelling at if you were an observer standing at the school. We can solve for $\vec{v}_\text{T}$ using the Pythagorean theorem and the tangent ratio.

Given: $\vec{v}_y = 12\ \text{km/h [N]};\ \vec{v}_x = 24\ \text{km/h [E]}$

Required: $\vec{v}_\text{T}$

Analysis: $\vec{v}_\text{T} = \vec{v}_y + \vec{v}_x$

Solution:
$$\begin{aligned}\vec{v}_\text{T} &= \vec{v}_y + \vec{v}_x\\ \vec{v}_\text{T} &= 12\ \text{km/h [N]} + 24\ \text{km/h [E]}\end{aligned}$$

Figure 14 shows the vector addition to determine the resultant velocity. This is the same technique we used in Tutorial 1.

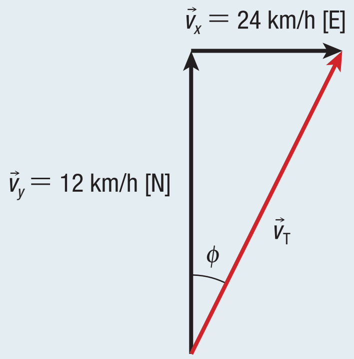


Figure 14 Determining the resultant velocity

$$\begin{aligned}v_\text{T}^2 &= v_y^2 + v_x^2\\ v_\text{T} &= \sqrt{v_y^2 + v_x^2}\\ v_\text{T} &= \sqrt{(12\ \text{km/h})^2 + (24\ \text{km/h})^2}\\ v_\text{T} &= 27\ \text{km/h}\end{aligned}$$

$$\begin{aligned}\tan\phi &= \frac{v_x}{v_y}\\ \tan\phi &= \frac{24\ \text{km/h}}{12\ \text{km/h}}\\ \phi &= 63^\circ\end{aligned}$$

Statement: The boat's resultant velocity is 27 km/h [N 63° E].

Practice

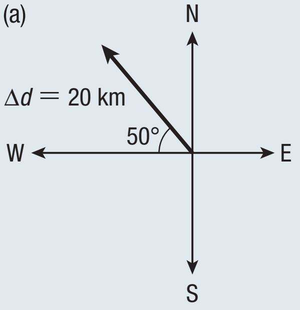
1. Write an email to a classmate explaining why the velocity of the current in a river has no effect on the time it takes to paddle a canoe across the river, as long as the boat is pointed perpendicular to the bank of the river. K/U C
2. A swimmer swims perpendicular to the bank of a 20.0 m wide river at a velocity of 1.3 m/s. Suppose the river has a current of 2.7 m/s [W]. T/I
   (a) How long does it take the swimmer to reach the other shore? [ans: 15 s]
   (b) How far downstream does the swimmer land from his intended location? [ans: 42 m [W]]

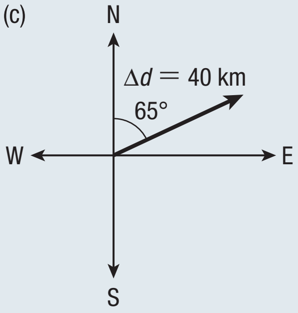
2.2 Summary

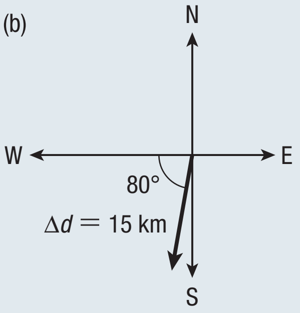
- Perpendicular vectors can be added algebraically using the Pythagorean theorem and the tangent function.
- By using the component method of vector addition, all vector addition problems can be converted into a problem involving two perpendicular vectors.
- River crossing problems involve two perpendicular, independent motions. You can solve these types of problems because the same time is taken for each motion.

2.2 Questions

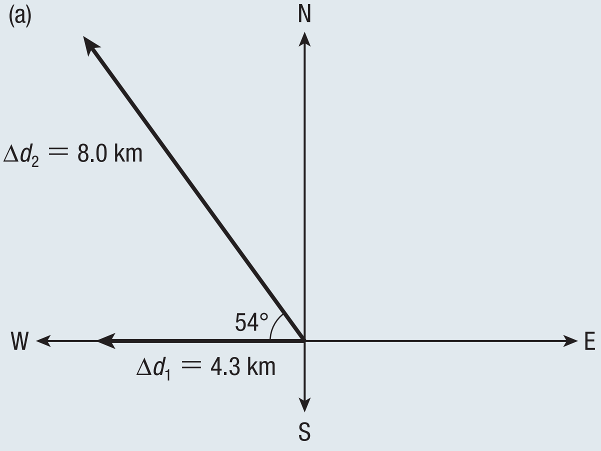
1. Break each vector down into an *x*-component and a *y*-component. T/I

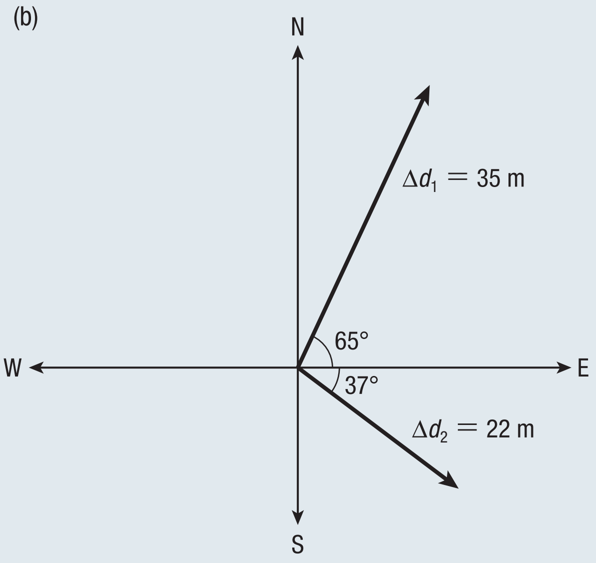






2. A motorcyclist drives 5.1 km [E] and then turns and drives 14 km [N]. What is her total displacement? T/I
3. A football player runs 11 m [N 20° E]. He then changes direction and runs 9.0 m [E]. What is his total displacement? T/I
4. What is the total displacement for a boat that sails 200.0 m [S 25° W] and then tacks (changes course) and sails 150.0 m [N 30° E]? T/I
5. Determine the total displacement of an object that travels 25 m [N 20° W] and then 35 m [S 15° E]. T/I
6. Use the component method to determine the total displacement given by the two vectors shown in each diagram.





7. Use the component method to add the following displacement vectors. T/I

$$\Delta\vec{d}_1 = 25\text{ m [N 30° W]},\ \Delta\vec{d}_2 = 30.0\text{ m [N 40° E]},$$
$$\Delta\vec{d}_3 = 35\text{ m [S 25° W]}$$

8. A swimmer jumps into a 5.1 km wide river and swims straight for the other side at 0.87 km/h [N]. There is a current in the river of 2.0 km/h [W]. T/I
   (a) How long does it take the swimmer to reach the other side?
   (b) How far downstream has the current moved her by the time she reaches the other side?
9. A conductor in a train travelling at 4.0 m/s [N] walks across the train car at 1.2 m/s [E] to validate a ticket. If the car is 4.0 m wide, how long does it take the conductor to reach the other side? What is his velocity relative to the ground? T/I
10. Vectors can be added algebraically and by scale diagram. C
    (a) Write a letter to your teacher explaining which method you prefer and why.
    (b) Describe a situation for which the method that you do not prefer might be more suitable.

2.3 Projectile Motion

Figure 1 An Olympic ski jumper uses his own body as a projectile.

How would you describe the motion of the Olympic ski jumper shown in **Figure 1** as he begins his ski jump? What path will his motion take as he falls toward the ground? The motion experienced by a ski jumper is identical to that of a ball thrown up in the air at an angle. Both travel through a two-dimensional curved path called a parabola. Any object that moves in response to gravity along a two-dimensional curved trajectory is called a **projectile**. The motion of a projectile under gravity is called **projectile motion**.

projectile an object that moves along a two-dimensional curved trajectory in response to gravity

projectile motion the motion of a projectile under gravity

Imagine you and a friend are standing in front of an open window. You each have an identical rubber ball. At the same instant, you throw your rubber ball horizontally out the window while your friend allows her rubber ball to just fall to the ground. Which rubber ball will reach the ground first? The answer may be surprising: both rubber balls will reach the ground at exactly the same time.

To understand this situation, recall how in river crossing problems the boat experiences two velocities that are perpendicular to each other. Since the velocity across the river and the velocity down the river have no effect on each other, these two velocities are independent.

In the example above, both rubber balls experience a vertical acceleration due to gravity. Although your rubber ball is projected horizontally, its horizontal motion does not affect its vertical motion. This is because the projectile's horizontal velocity is perpendicular to its vertical velocity. These two velocities are independent of each other. **Figure 2** shows that the horizontal velocity does not change, while the vertical velocity increases from zero with uniform acceleration. The rubber ball that you throw horizontally will experience the same vertical motion as the rubber ball that falls straight down. As a result, both rubber balls reach the ground at the same time. The amount of time it takes for a projectile to complete its motion is known as its **time of flight**.

time of flight the time taken for a projectile to complete its motion

Investigation 2.3.1

Modelling Projectile Motion (p. 86)
In this investigation, you will launch projectiles horizontally from various heights and analyze your results using what you have learned about projectile motion.

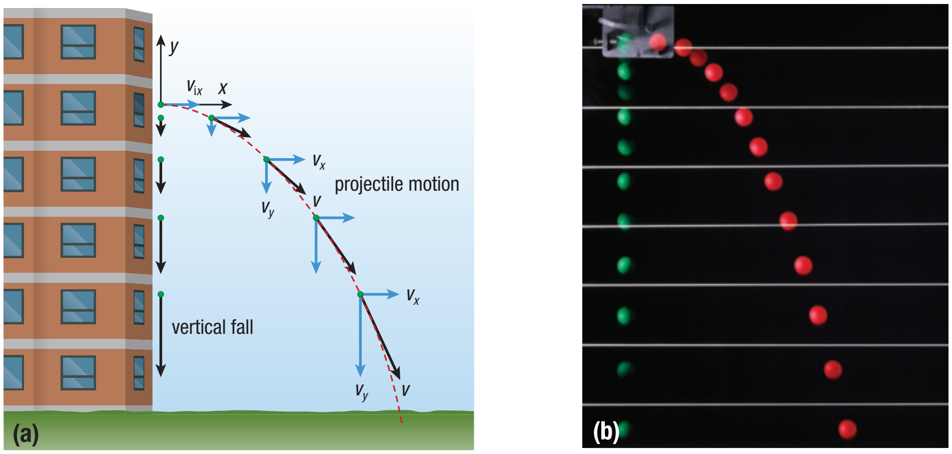


Figure 2 (a) The motion of one rubber ball dropped and the second rubber ball projected horizontally at a constant speed from the same height (b) A time-lapse image of one ball dropped and the other projected horizontally

LEARNING TIP

x*, *y*, and *t
In projectile motion problems, it is helpful to remember that time, *t*, is a scalar variable and is different from either the *x*-variable or the *y*-variable describing the two-dimensional vectors of displacement, velocity, and acceleration.

There is, however, one key difference between a river crossing problem and the projectile motion problem described above. In a river crossing problem both velocities are constant. In a projectile motion problem, while the horizontal velocity is constant, the vertical velocity changes because of the acceleration due to gravity. The rubber ball that you throw is simultaneously undergoing uniform velocity horizontally and uniform acceleration vertically. These two motions are independent of each other, but once again they do share one common factor: time. The time taken for the horizontal motion is exactly the same as the time taken for the vertical motion. This is true since the projectile comes to rest when it hits the ground. The horizontal distance travelled by a projectile (Δd_x) is known as the **range**.

range the horizontal distance travelled by a projectile

Describing Projectile Motion

Projectile motion problems are two-dimensional vector problems. To describe motion in this type of problem in terms of vectors, we will use the convention that velocity vectors pointing upward or to the right have positive values and velocity vectors pointing downward or to the left have negative values (**Figure 3**).

One of the techniques that we will use in solving projectile motion problems is to work with motion in only one direction (horizontal or vertical) at a time. By doing so, we will use information provided about motion in one direction to solve for a time value. This time value can then be used to calculate values for the other direction.

One of the simplest types of projectile motion is when an object is projected horizontally from a known height. This scenario is covered in Tutorial 1. In Tutorial 2, we will consider the case when an object is projected at an angle to the horizontal.

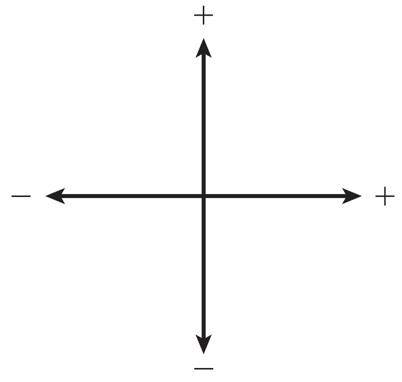


Figure 3 Sign conventions for projectile motion

Tutorial 1 Launching a Projectile Horizontally

Since we will be working with only one motion at any given time, we will not use vector arrows in these problems. Remember, however, that projectile motion problems are vector problems. When a projectile is launched horizontally, it has an initial velocity $\vec{v}_{ix}$ in the horizontal direction. The initial velocity in the vertical direction $\vec{v}_{iy}$ is equal to zero.

Sample Problem 1

A beanbag is thrown from a window 10.0 m above the ground with an initial horizontal velocity of 3.0 m/s.

(a) How long will it take the beanbag to reach the ground? That is, what is its time of flight?

(b) How far will the beanbag travel horizontally? That is, what is its range?

Solution

(a) To determine the time of flight of the beanbag, consider its vertical motion.

Given: $\Delta d_y = -10.0$ m; $a_y = -9.8$ m/s^2; $v_{iy} = 0$ m/s

Required: Δt

Analysis: We can use one of the five motion equations from Section 1.5 to solve for the time it takes the beanbag to reach the ground:

$$\Delta d_y = v_{iy}\Delta t + \frac{1}{2}a_y\Delta t^2$$

Solution: In **Figure 4**, notice how the beanbag undergoes motion in the shape of a parabola. Notice also that in the given statement, the vertical displacement is shown as negative. This indicates that the beanbag is falling downward. Similarly, acceleration due to gravity is given as negative. The initial velocity in the vertical direction (v_{iy}) is zero because the beanbag is not thrown upward or downward.

$$\Delta d_y = v_{iy}\Delta t + \frac{1}{2}a_y\Delta t^2$$

$$= 0 + \frac{1}{2}a_y\Delta t^2$$

$$\Delta d_y = \frac{a_y\Delta t^2}{2}$$

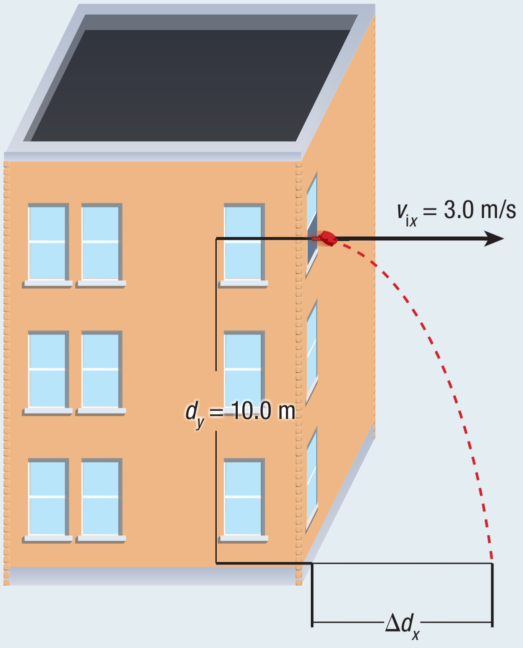


Figure 4 Projectile motion, launching horizontally

$$\Delta t = \sqrt{\frac{2\Delta d_y}{a_y}}$$

$$= \sqrt{\frac{2(-10.0\ \cancel{m})}{-9.8\frac{\cancel{m}}{s^2}}}$$

$$\Delta t = 1.43\ s$$

Statement: It takes 1.4 s for the beanbag to reach the ground.

Notice that an extra digit has been included in the calculated answer for Δt. This is because the value of Δt will be used in the next calculation, and we wish to minimize rounding error.

(b) To determine the beanbag's horizontal distance or range, we will consider its horizontal motion. We will use the fact that both motions, vertical and horizontal, take the same amount of time.

Given: $\Delta t = 1.43$ s; $v_{ix} = 3.0$ m/s; $a_x = 0$ m/s^2

Notice that the time value is the same as for the vertical motion. The horizontal acceleration is zero, since the beanbag is not experiencing any force in the horizontal direction.

Required: Δd_x

Analysis: $\Delta d_x = v_{ix}\Delta t$

Solution: $\Delta d_x = v_{ix}\Delta t$

$$= (3.0\ \text{m/s})(1.43\ \text{s})$$

$$\Delta d_x = 4.3\ \text{m}$$

Statement: The beanbag travels 4.3 m horizontally.

Practice

1. A hockey puck is launched horizontally from the roof of a 32 m tall building at a velocity of 8.6 m/s. T/I
   (a) What is the hockey puck's time of flight? [ans: 2.6 s]
   (b) What is the hockey puck's range? [ans: 22 m]
2. Suppose the hockey puck in Question 1 has an initial velocity one-half the value given. How does this affect the puck's time of flight and range? K/U

You can increase the range of the beanbag in Tutorial 1 by projecting it partially upward instead of horizontally. In other words, you can give v_{iy} and v_{ix} values other than zero. By doing so, you can increase the time of flight for the projectile. Since the projectile is moving horizontally at a constant velocity, increasing the time of flight can increase the horizontal displacement. This is why competitive swimmers begin their races by diving slightly upward as well as forward. Increasing the launch angle also decreases the horizontal velocity, however. So if you choose too large an angle, you may find that the range of your projectile actually decreases (**Figure 5**).

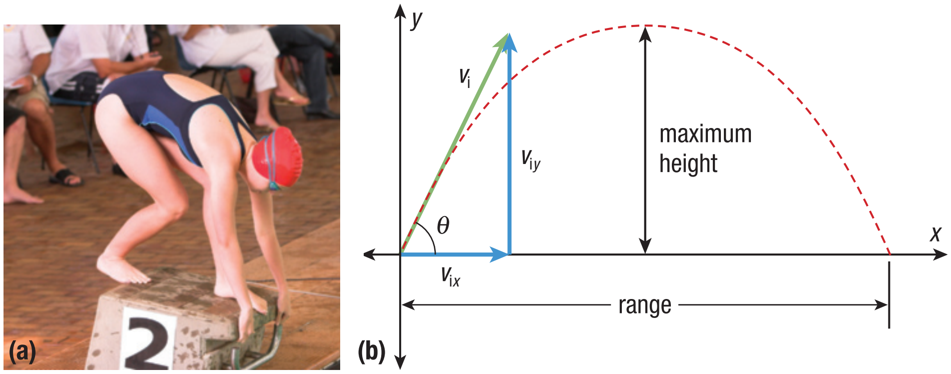


Figure 5 (a) A competitive swimmer (b) Competitive swimmers judge their launch angle carefully to maximize their range before entering the pool.

Tutorial 2 Launching a Projectile at an Angle to the Horizontal

Projectiles that are launched at an angle to the horizontal also undergo parabolic motion. The calculations in this tutorial are similar to those in Tutorial 1. The main difference is that the projectile has an initial velocity in the vertical direction (v_{iy}). This is because the object is launched at an angle rather than horizontally.

Sample Problem 1

A soccer player running on a level playing field kicks a soccer ball with a velocity of 9.4 m/s at an angle of 40° above the horizontal. Determine the soccer ball's

(a) time of flight
(b) range
(c) maximum height

Figure 6 shows the soccer ball being kicked from ground level, undergoing parabolic motion, and eventually landing back on the ground. Notice that for this situation the total vertical displacement of the ball (Δd_y) is zero.

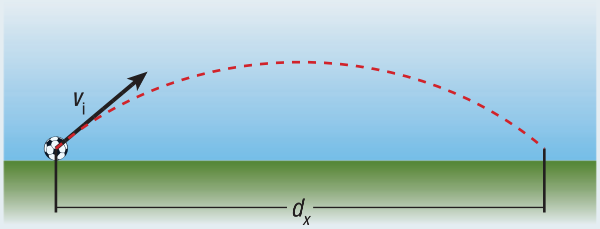


Figure 6 Motion of the soccer ball

Figure 7 shows the initial velocity of the ball broken down into its vertical and horizontal components. We can determine the magnitude of these two components by recalling that $v_{ix} = v_i \cos 40°$ and $v_{iy} = v_i \sin 40°$.

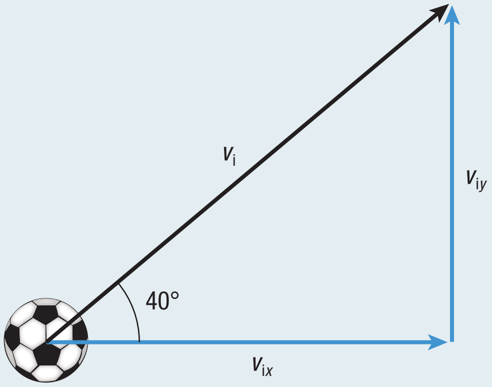


Figure 7 Components of the initial velocity

(a) Consider the soccer ball's vertical motion:

Given: $\Delta d_y = 0\text{ m};\ a_y = -9.8\text{ m/s}^2;\ v_i = 9.4\text{ m/s}$

Required: time of flight

Analysis: $\Delta d_y = v_{iy}\Delta t + \frac{1}{2}a_y\Delta t^2$

Solution:
$$\Delta d_y = v_{iy}\Delta t + \frac{1}{2}a_y\Delta t^2$$
$$0 = v_i(\sin 40°)\Delta t + \frac{1}{2}a_y\Delta t^2$$
$$0 = v_i(\sin 40°) + \frac{1}{2}a_y\Delta t,\ \ \Delta t \neq 0$$

(dividing both sides by Δt)

$$\frac{a_y\Delta t}{2} = -v_i(\sin 40°)$$
$$\Delta t = \frac{-2v_i(\sin 40°)}{a_y}$$
$$= \frac{-2(9.4\text{ m/s})(\sin 40°)}{-9.8\text{ m/s}^2}$$
$$\Delta t = 1.233\text{ s}$$

Statement: The soccer ball's time of flight is 1.2 s.

(b) Consider the horizontal motion:

Given: $\Delta t = 1.233\text{ s};\ v_i = 9.4\text{ m/s};\ a_x = 0\text{ m/s}^2$

Required: Δd_x

Analysis: Since the ball is travelling at a constant velocity horizontally, we can use the defining equation for average velocity to calculate the range.

$$\Delta d_x = v_{ix}\Delta t$$

Solution:
$$\Delta d_x = v_{ix}\Delta t$$
$$= v_i(\cos 40°)\Delta t$$
$$= \left(9.4\,\frac{\text{m}}{\cancel{\text{s}}}\right)(\cos 40°)(1.233\ \cancel{\text{s}})$$
$$\Delta d_x = 8.9\text{ m}$$

Statement: The soccer ball's range is 8.9 m.

(c) We can analyze the vertical motion to determine the maximum height of the ball. If we only consider the motion of the ball on its way up to its maximum height, we know its initial velocity and its acceleration. We also know that at its maximum height, the ball will come to rest in the vertical or *y*-direction. As a result, its final vertical velocity (v_{fy}) (considering the motion only as far as the maximum height reached) is zero.

Consider the vertical motion:

Given: $a_y = -9.8\text{ m/s}^2;\ v_i = 9.4\text{ m/s};\ v_{fy} = 0\text{ m/s}$

Required: Δd_y

Since the ball is undergoing uniform vertical acceleration, we can use one of the five key kinematics equations to solve for the vertical displacement at maximum height.

Analysis: $v_{fy}^2 = v_{iy}^2 + 2a_y\Delta d_y$

Solution:
$$v_{fy}^2 = v_{iy}^2 + 2a_y\Delta d_y$$
$$0 = v_{iy}^2 + 2a_y\Delta d_y$$
$$\Delta d_y = \frac{-v_{iy}^2}{2a_y}$$
$$= \frac{-[(9.4\text{ m/s})(\sin 40°)]^2}{2(-9.8\text{ m/s}^2)}$$
$$\Delta d_y = 1.9\text{ m}$$

Statement: The soccer ball's maximum height is 1.9 m.

The most complex type of projectile motion problem combines the previous two problem types. In this situation the projectile is launched at an angle from a height above the ground and lands at another height. This is the scenario that we will consider in the next Sample Problem.

Sample Problem 2

A golfer is trying to improve the range of her shot. To do so she drives a golf ball from the top of a steep cliff, 30.0 m above the ground where the ball will land. If the ball has an initial velocity of 25 m/s and is launched at an angle of 50° above the horizontal, determine the ball's time of flight, its range, and its final velocity just before it hits the ground. **Figure 8** shows the motion of the golf ball.

For this solution we will combine the horizontal and vertical given statements.

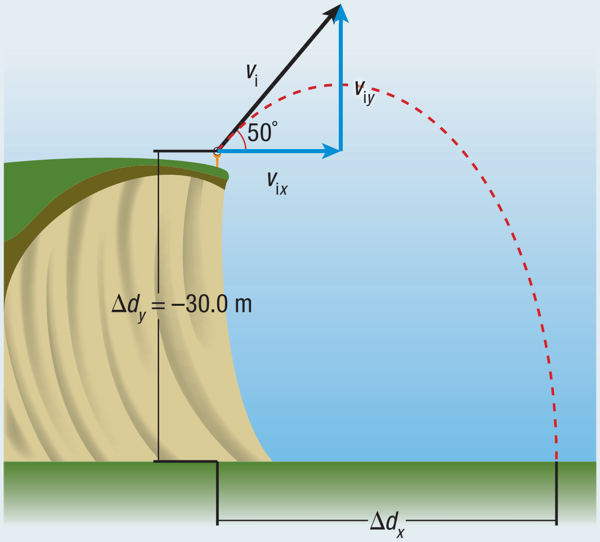


Figure 8 Motion of the golf ball

Given: $\Delta d_y = -30.0$ m; $a_y = -9.8$ m/s^2; $v_i = 25$ m/s; $a_x = 0$ m/s^2; $\theta = 50°$

To determine the horizontal range, we first need to determine the time of flight. Consider the vertical motion.

Required: Δt

Analysis: $\Delta d_y = v_{iy}\Delta t + \frac{1}{2}a_y\Delta t^2$

Notice that this is a quadratic equation for time. Previously, whenever we needed to solve this equation for time, one of the variables in this equation was equal to zero. This allowed us to solve for Δt without having to solve a quadratic equation. In this more complicated case it is necessary to solve the quadratic equation. We must therefore expand this equation and use the quadratic formula. To simplify the calculation, we will ignore the units until the end.

Solution: $\Delta d_y = v_{iy}\Delta t + \frac{1}{2}a_y\Delta t^2$

$$= v_i(\sin\theta)\Delta t + \frac{1}{2}a_y\Delta t^2$$

$$-30.0 = 25\sin 50°\Delta t + \frac{1}{2}(-9.8)\Delta t^2$$

$$0 = -4.9\Delta t^2 + 19.2\Delta t + 30.0$$

$$\Delta t = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$\Delta t = \frac{-19.2 \pm \sqrt{(19.2)^2 - 4(-4.9)(30.0)}}{2(-4.9)}$$

$$= \frac{-19.2 \pm 30.930}{-9.8}$$

$$\Delta t = -1.197 \text{ s} \text{ or } \Delta t = 5.115 \text{ s (two extra digits carried)}$$

We will take the positive root because negative time has no meaning in this context.

Statement: The golf ball's time of flight is 5.1 s.

To determine the range, consider the horizontal motion:

Required: Δd_x

Analysis: $\Delta d_x = v_{ix}\Delta t$

Solution: $\Delta d_x = v_i(\cos 50°)\Delta t$

$$= (25 \text{ m/s})(\cos 50°)(5.11 \text{ s})$$

$$\Delta d_x = 82 \text{ m}$$

Statement: The range of the golf ball is 82 m.

To determine the final velocity of the ball just before it hits the ground, consider **Figure 9**. This figure shows the final velocity of the ball as well as its horizontal and vertical components. Since the golf ball was travelling at a constant horizontal velocity, we know that the final horizontal velocity (v_{fx}) equals the initial horizontal velocity (v_{ix}). In the vertical direction, however, the initial and final velocities are not the same since the golf ball is accelerating vertically.

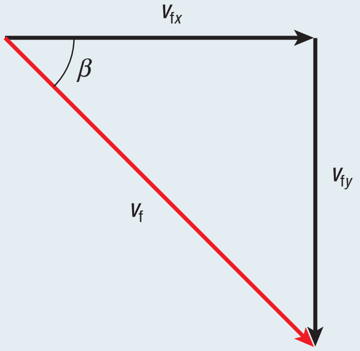


Figure 9 Determining the final velocity

Consider the horizontal motion:

$$v_{fx} = v_{ix}$$

$$= v_i \cos 50°$$

$$= (25 \text{ m/s}) \cos 50°$$

$$v_{fx} = 16.1 \text{ m/s}$$

Consider the vertical motion:

$$v_{fy}^2 = v_{iy}^2 + 2a_y\Delta d_y$$

$$v_{fy} = \sqrt{v_{iy}^2 + 2a_y\Delta d_y}$$

$$= \sqrt{(v_i \sin 50°)^2 + 2a_y\Delta d_y}$$

$$= \sqrt{[(25 \text{ m/s})(\sin 50°)]^2 + 2(-9.8 \text{ m/s}^2)(-30.0 \text{ m})}$$

$$v_{fy} = 30.9 \text{ m/s}$$

We can then determine the final velocity by using the Pythagorean theorem and the inverse tangent function:

$$v_f^2 = v_{fx}^2 + v_{fy}^2$$

$$v_f = \sqrt{v_{fx}^2 + v_{fy}^2}$$

$$= \sqrt{(16.1\text{ m/s})^2 + (30.9\text{ m/s})^2}$$

$$v_f = 35\text{ m/s}$$

$$\tan\beta = \frac{v_{fy}}{v_{fx}}$$

$$\tan\beta = \frac{30.9\text{ m/s}}{16.1\text{ m/s}}$$

$$\beta = 62°$$

$$\vec{v}_f = 35\text{ m/s [right 62° down]}$$

Statement: The golf ball's final velocity is 35 m/s [right 62° down].

Practice

1. A superhero launches himself from the top of a building with a velocity of 7.3 m/s at an angle of 25° above the horizontal. If the building is 17 m high, how far will he travel horizontally before reaching the ground? What is his final velocity? [ans: 15 m; 20 m/s [right 70° down]] T/I
2. Two identical baseballs are initially at the same height. One baseball is thrown at an angle of 40° above the horizontal. The other baseball is released at the same instant and is allowed to fall straight down. Compare the amount of time it takes for the two baseballs to reach the ground. Explain your answer. K/U C

2.3 Summary

- Projectile motion consists of independent horizontal and vertical motions.
- The horizontal and vertical motions of a projectile take the same amount of time.
- Projectiles move horizontally at a constant velocity. Projectiles undergo uniform acceleration in the vertical direction. This acceleration is due to gravity.
- Objects can be projected horizontally or at an angle to the horizontal. Projectile motion can begin and end at the same or at different heights.
- The five key equations of motion can be used to solve projectile motion problems. The time of flight, range, and maximum height can all be determined given the initial velocity and the vertical displacement of the projectile.

UNIT TASK **BOOKMARK**

You can use what you have learned about angle of projection and range to calibrate your launcher in the Unit Task on page 96.

2.3 Questions

1. What do the horizontal and vertical motions of a projectile have in common? K/U
2. A tennis ball thrown horizontally from the top of a water tower lands 20.0 m from the base of the tower. If the tennis ball is initially thrown at a velocity of 10.0 m/s, how high is the water tower? How long does it take the tennis ball to reach the ground? T/I
3. At what angle should you launch a projectile from the ground so that it has the
   (a) greatest time of flight?
   (b) greatest range, assuming no air resistance? (Hint: Use your findings from Investigation 2.3.1) K/U
4. A field hockey ball is launched from the ground at an angle to the horizontal. What are the ball's horizontal and vertical accelerations
   (a) at its maximum height?
   (b) halfway up to its maximum height?
   (c) halfway down to the ground? K/U
5. An archer shoots at a target 60 m away. If she shoots at a velocity of 55 m/s [right] from a height of 1.5 m, does the arrow reach the target before striking the ground? What should the archer do to get her next shot on target? T/I C
6. An acrobat is launched from a cannon at an angle of 60° above the horizontal. The acrobat is caught by a safety net mounted horizontally at the height from which he was initially launched. Suppose the acrobat is launched at a speed of 26 m/s. T/I
   (a) How long does it take before he reaches his maximum height?
   (b) How long does it take in total for him to reach a point halfway back down to the ground?
7. A championship golfer uses a nine iron to chip a shot right into the cup. If the golf ball is launched at a velocity of 20 m/s at an angle of 45° above the horizontal, how far away was the golfer from the hole when he hit the ball? What maximum height did the ball reach? T/I
8. As part of a physics investigation, a student launches a beanbag out of an open window with a velocity of 4.5 m/s at an angle of 25° above the horizontal. If the window is 12 m above the ground, how far away from the building must the student's friend stand to catch the beanbag at ground level? T/I

Galileo Galilei: Sixteenth-Century "New Scientist"

ABSTRACT

SKILLS HANDBOOK A4

Galileo Galilei was a sixteenth-century scientist who challenged the teachings of ancient philosophers by performing experiments to test their theories. This was a radical new way of doing science. Galileo performed an experiment that involved rolling spheres down a ramp. The results of this experiment disproved Aristotle's theory that objects fall at constant speeds, but more massive objects fall faster than less massive objects. Galileo proved that the motion of an object in free fall does not depend on the mass of the object. He has made many important contributions to science.

Introduction

Science is constantly changing. Every new advance or discovery changes the way that we look at the world around us, and sometimes the way we look at science itself. In the early 1500s "science" was dictated according to a small group of ancient philosophers whose teachings were considered to be unquestionable. Those who questioned the 2000-year-old teachings of Aristotle and Plato were considered foolish, rebellious, and a threat to the "established order."

Galileo Galilei (**Figure 1**) was born near Pisa, Italy, in 1564. A very bright and ambitious young man with a gift for scientific inquiry, Galileo pushed the boundaries of what was considered to be acceptable. Powerful authorities strongly supported Aristotle's scientific views.

Figure 1 Galileo (1564–1642)

Aristotle taught that there are two kinds of motion for inanimate matter: "natural" and "unnatural." Natural motion, without acceleration, occurs when objects seek their natural place in the universe. Unnatural motion occurs when a force is applied on an object. According to Aristotle, a stone falls (natural motion) until it reaches its natural place on Earth. Aristotle also wrote that massive objects should fall faster than less massive objects. In the 1500s, it was dangerous to challenge Aristotle's ideas and took a lot of courage to do so.

It is said that Galileo first began to question Aristotle's views on falling objects while observing a hailstorm. He noticed that large hailstones struck the ground at the same time as small hailstones. If Aristotle was correct, this could only occur if the large hailstones were created higher in the atmosphere than the small hailstones. Galileo found this very difficult to believe. A more reasonable explanation was that hailstones were all created at approximately the same height and fell at the same rate, regardless of mass. These thoughts led Galileo to attempt to test Aristotle's teachings.

Galileo's Legendary Experiment

The legend goes that Galileo dropped a cannonball and a much less massive musket ball from the top of the Leaning Tower of Pisa. Both the cannonball and the musket ball struck the ground at the same time. Galileo probably never performed this experiment himself, but a similar experiment had already been published by Benedetti Giambattista in 1553. More recently, in 1971, astronaut David Scott performed this experiment on the Moon (where there is virtually no air resistance) by dropping a hammer and a feather from the same height. Both the hammer and the feather struck the ground at the same time.

In 1638 Galileo Galilei published a book called *Discourses and Mathematical Demonstrations Relating to Two New Sciences*. In this book, Galileo described his ideas about falling bodies and projectile motion, which are still a key part of kinematics. He used experimental observation and mathematical reasoning to explain the behaviour of objects. This was a relatively new way of doing science. Philosophers like Aristotle and Plato had relied upon pure reason and logic to create scientific theories. The publication of *Two New Sciences* coincided with the beginning of the modern era of science, in which our description of the physical world is based on experimental evidence, not the views of those in positions of authority.

Do Falling Objects Accelerate?

Galileo set out to prove that falling objects accelerated. He hypothesized, "We may picture to our mind a motion as uniformly and continuously accelerated when, during any equal intervals of time whatever, equal increments of speed are given to it." Proving this was very difficult because the technology of the day was quite basic. Galileo knew that free-falling objects increase their speed far too quickly to be measured accurately. To simplify matters, he chose to study how balls rolled down inclined planes (ramps). In *Two New Sciences*, Galileo described the results of his experiment:

> Having performed this operation and having assured ourselves of its reliability, we now rolled the ball only one-quarter the length of the channel; and having measured the time of its descent, we found it precisely one-half of the former. Next we tried other distances, compared the time for the whole length with that for the half, or with that for two-thirds, or three-fourths, or indeed for any fraction; in such experiments, repeated a full hundred times, we always found that the spaces traversed were to each other as the squares of the times, and this was true for all inclinations of the plane, i.e., of the channel, along which we rolled the ball.

Had the ball been travelling at a constant speed, the distance travelled would have been directly proportional to the time measured. Instead, Galileo observed that the distance travelled was proportional to the time squared. He had proven that falling objects accelerate. This would eventually lead to one of the five key motion equations:

$$\Delta\vec{d} = \vec{v}_i\Delta t + \frac{1}{2}\vec{a}_{av}\Delta t^2$$

Galileo's contributions to science are incredible. **Figure 2** is a photograph taken by the Cassini spacecraft in 2000 showing one of the four large moons Galileo discovered orbiting Jupiter. Galileo helped set the stage for the future of science, where truth and understanding are based on reproducible experimental evidence. In fact Albert Einstein said, "… all knowledge of reality starts from experience and ends in it. Propositions arrived at by purely logical means are completely empty as regards reality. Because Galileo saw this, and particularly because he drummed it into the scientific world, he is the father of modern physics—indeed, of modern science altogether."

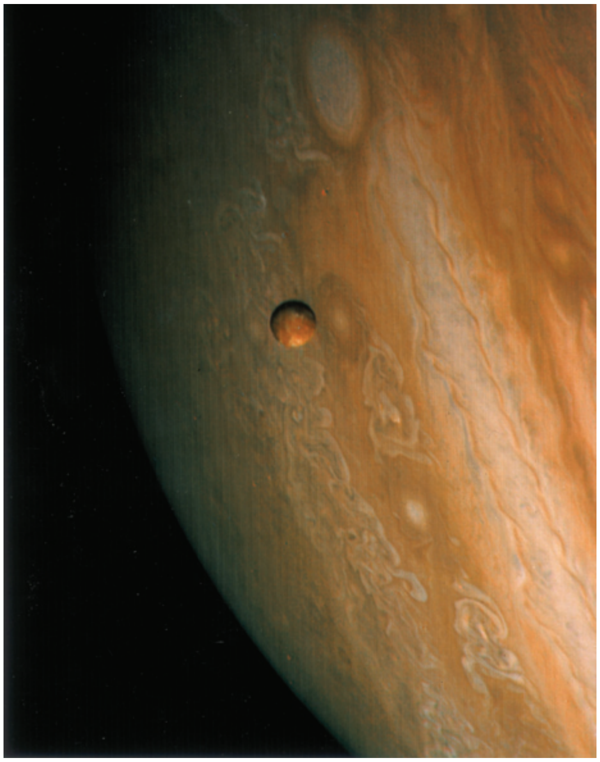


Figure 2 Io, one of the four largest moons of Jupiter (also called the Galilean moons)

Further Reading

Drake, S. (1990). *Galileo: Pioneer scientist*. Toronto: University of Toronto Press.

Einstein, A. (1954). *Ideas and opinions*. New York: Crown Publishers, Inc.

Galilei, G. (reprinted 1974). *Two new sciences; including centers of gravity & force of percussion*. Madison: University of Wisconsin Press.

GO TO NELSON SCIENCE

2.4 Questions

1. In your own words, explain why Albert Einstein considered Galileo to be the "father of modern science." K/U
2. Why did Galileo choose to use a ramp to perform his acceleration experiment? K/U
3. Conduct research to explore other scientific discoveries made by Galileo. Provide one example. T/I
4. List three other scientific theories that have recently challenged conventional scientific thought. K/U
5. Conduct research into how authorities in the sixteenth and seventeenth centuries responded to Galileo's experiments and published works. Provide one example. T/I

GO TO NELSON SCIENCE

2.5 Explore Applications in Kinematics

SKILLS MENU

- Researching
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating
- Identifying Alternatives

Accelerometers: Accelerating Your Life

Have you ever used a touchscreen phone or played a video game with a remote controller? Have you wondered how these devices convert the movement of the device to motion on the screen? Touchscreen phones and video games use accelerometers to measure acceleration, or how quickly something is moving in a particular direction (**Figure 1**). Accelerometers found in ordinary laptop computers have even been used to create a broad-area earthquake detection system.

Figure 1 Accelerometers can increase functionality and even entertainment value.

An accelerometer is a device that measures acceleration. Electronic accelerometers are tiny devices made of semi-conducting material that may be only a couple of millimetres in length (**Figure 2**). These devices can be manufactured inexpensively and are found in many of the devices that you use every day. Despite their common use, many people are unaware of how frequently they come in contact with accelerometers, and of how accelerometers make their lives safer, more convenient, and more fun.

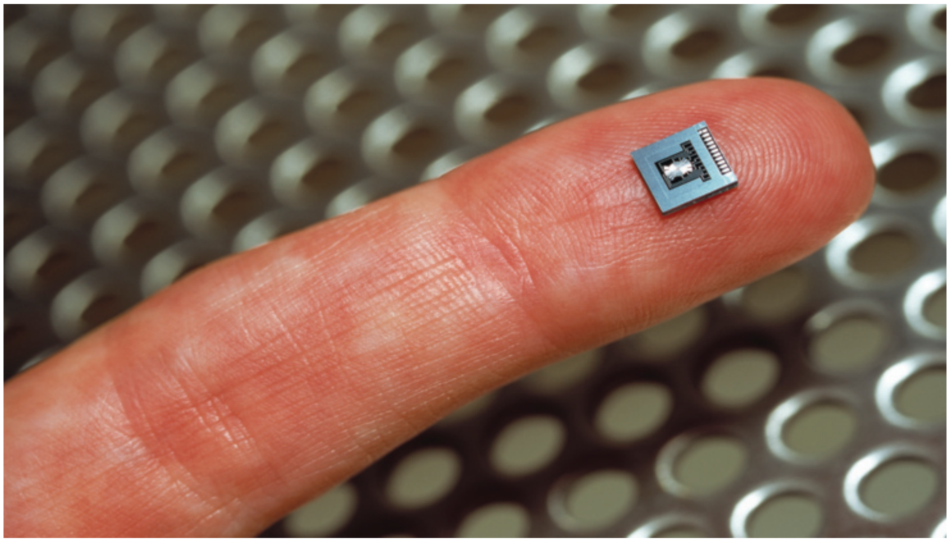


Figure 2 An electronic 3-D accelerometer

The Application

Electronic accelerometers have applications in many different fields. They are used in navigation, medicine, engineering, transportation, building and structural monitoring, mobile phones, and other electronic devices. Simple accelerometers can be used to measure acceleration in one direction. More complex devices can measure acceleration in two or three directions. Accelerometers can also be used to measure the tilt and position of an object.

Specific applications include navigating menus on a screen, camera stabilization, 3-D object manipulation, screen rotation, gestures such as pretending to cast a fishing rod or swing a tennis racket, and power conservation.

Your Goal

To discover how accelerometers are used in a device that has had an impact on your life, and communicate your findings to a Grade 9 science class

Research

Working in pairs or small groups, perform some initial research to find a device that contains an accelerometer. Once you have chosen a device, use the following questions to guide your research:

- How does the accelerometer work in the device you chose?
- How does the accelerometer function as part of the design of the device you chose?
- What are the advantages and disadvantages for a consumer of purchasing the device you chose, with or without the accelerometer? Consider the cost of the accelerometer and how well the device would work without the accelerometer.
- What are the societal and environmental impacts of the device you chose? (For example, what materials are used in manufacturing it? Does it use batteries that are difficult to dispose of safely?) Does the use of the accelerometer affect the impact of your chosen device?

WEB LINK

To learn more about accelerometers,

GO TO NELSON SCIENCE

Summarize

As a group, summarize your research and make a conclusion about the overall impact of accelerometers.

Communicate

You are to communicate the findings of your research to a Grade 9 science class. You and your partner or group may present your findings in the form of a brochure, an electronic slide presentation, a video presentation, a bulletin board, a newsletter article, or a television advertisement. Remember, you want your audience to understand how accelerometers work and how they have improved the functionality of the devices in which they are used.

CAREER LINK

Teachers must communicate effectively to help students understand science and technology. To learn more about becoming a science teacher,

GO TO NELSON SCIENCE

Investigation 2.3.1 CONTROLLED EXPERIMENT

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Modelling Projectile Motion

In Section 2.3, you studied projectiles launched in a number of different scenarios. In this experiment you will launch projectiles horizontally from various heights to see how well projectile motion theory predicts your results.

Testable Question

How does changing the vertical displacement of a projectile affect its range and time of flight?

Hypothesis/Prediction

After reading through the Experimental Design and Procedure, predict an answer to the Testable Question. Your hypothesis should include predictions and reasons for your prediction.

Variables

Identify the controlled, manipulated, and responding variables in this experiment.

Experimental Design

In this experiment, you will roll spheres down a ramp in order to launch them horizontally from various heights (**Figure 1**). By varying the height from which your projectile is launched, you will determine how changing a projectile's vertical displacement affects its time of flight and range.

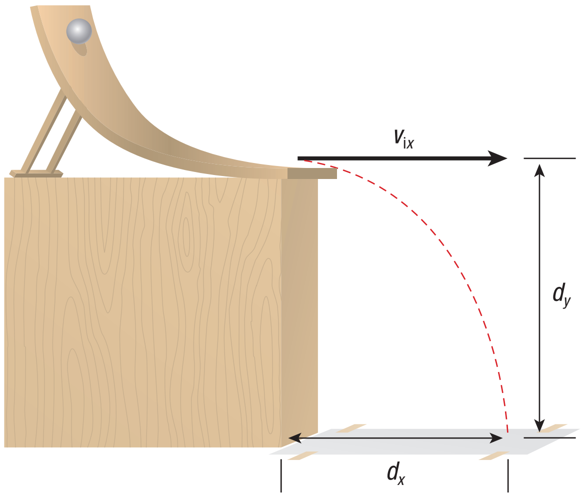


Figure 1

Equipment and Materials

- C-clamp
- ramp
- wooden board
- plumb bob
- metal sphere
- metre stick
- bricks, wooden blocks, or textbooks
- masking tape
- sheet of newsprint
- sheet of carbon paper

Procedure

SKILLS HANDBOOK A6.2

1. Use the C-clamp to secure the ramp to the wooden board. Place the ramp and board on a lab bench, box, or table.
2. Use masking tape to secure the newsprint to the floor below the ramp. You might want to roll the ball down the ramp once to see where it lands before securing the newsprint.
3. Hang the plumb bob over the end of the wooden board. Adjust the plumb bob so that it just touches the floor. Mark the position of the plumb bob on the sheet of newsprint. This point will represent the end of your ramp. This will mark the starting point for the projectile's horizontal motion. The projectile is the metal sphere.
4. Place the carbon paper on top of the newsprint with the carbon side facing down.
5. Roll the sphere down the ramp and off the end of the wooden board, allowing it to strike the floor and produce a dot on the carbon paper.
6. Repeat Step 5 nine more times to produce a cluster of dots on the newsprint.
7. Check the size of your cluster of dots. The cluster should be no larger than the size of a quarter. If it is larger, modify your technique to reduce the size of your cluster of dots.

8. Copy **Table 1** into your notebook. You will use this data table to record vertical displacement and horizontal displacement (range), and to enter calculated values. Create five rows for five trials.

Table 1 Data Table for Investigation

<table>
<tr><th colspan="5">Initial velocity (v_{ix}) =</th></tr>
<tr><th>Trial number</th><th>Vertical displacement (m)</th><th>Theoretical time of flight (s)</th><th>Theoretical range (m)</th><th>Experimental range (m)</th></tr>
<tr><td></td><td></td><td></td><td></td><td></td></tr>
</table>

9. Measure the vertical displacement of the projectile by measuring the vertical distance from the floor to the centre of the sphere while it is sitting on the end of the ramp. Enter this value in your data table.

10. Measure the horizontal displacement of the projectile by measuring the distance from the point where the plumb bob makes contact with the newsprint to the centre of the cluster formed by the dots. Enter this value in your data table under "Experimental Range."

11. If your technique is consistent, the sphere will always be projected from the end of the ramp at the same velocity. Now that you have measured the horizontal and vertical displacement for your first trial, use these values to calculate the initial horizontal velocity of the projectile. Consider the horizontal motion of the projectile:

$$\Delta d_x = v_{ix}\Delta t$$

$$\Delta t = \frac{\Delta d_x}{v_{ix}} \qquad \text{Equation 1}$$

Since all projectiles in this experiment are launched horizontally, the initial vertical velocity is zero. As such, the vertical motion of your projectile can be described by

$$\Delta d_y = \frac{1}{2}a_y\Delta t^2 \qquad \text{Equation 2}$$

Substitute Equation 1 into Equation 2 to get

$$\Delta d_y = \frac{1}{2}a_y\left(\frac{\Delta d_x}{v_{ix}}\right)^2$$

$$\Delta d_y = \frac{a_y\Delta d_x^{\,2}}{2\,v_{ix}^{\,2}}$$

$$v_{ix} = \sqrt{\frac{a_y\Delta d_x^2}{2\Delta d_y}} \qquad \text{Equation 3}$$

Equation 3 will allow you to calculate the initial velocity of the projectile. Remember that this velocity will be constant throughout the experiment.

12. Place textbooks under the board on which you have mounted your ramp to increase the board's height.

13. Mark the position of the plumb bob on the newsprint.

14. Measure the new vertical displacement and enter this value in your data table.

15. Roll the metal sphere down the ramp 10 times to create a new cluster of dots. Measure the horizontal displacement based on the centre of the cluster from the plumb bob and enter this value in your data table.

16. To calculate the theoretical time of flight for the ball's motion, consider the vertical motion of the projectile. Rearrange Equation 2 to get Δt:

$$\Delta d_y = \frac{1}{2}a_y\Delta t^2$$

$$\frac{2\Delta d_y}{a_y} = \Delta t^2$$

$$\Delta t = \sqrt{\frac{2\Delta d_y}{a_y}}$$

Use this equation and the fact that $ay = g$ to calculate the theoretical time of flight for the projectile. Enter this value in your data table.

17. Calculate the theoretical range of the projectile using the equation $\Delta d_x = v_{ix}\Delta t$. Enter this value in your data table.

18. Repeat Steps 12 to 17 for three other heights.

Analyze and Evaluate

(a) Answer the Testable Question. K/U

(b) Write a statement that describes the relationship between vertical displacement and theoretical time of flight. T/I C

(c) Write a statement that describes the relationship between vertical displacement and theoretical range. T/I C

(d) How did your theoretical range values compare to your experimental range values? T/I

(e) Describe any sources of uncertainty that may have affected your experiment. T/I

(f) If you were to repeat this experiment, what would you do to reduce the uncertainty? T/I

(g) What evidence is there to support or refute your prediction? T/I

Apply and Extend

(h) Using the same equipment, how could you modify this experiment to study other projectile motion scenarios? A

UNIT TASK **BOOKMARK**

You can apply what you have learned about projectile motion to the Unit Task on page 96.

CHAPTER 2 SUMMARY

Summary Questions

1. Create a study guide based on the points listed in the margin on page 58. For each point, create three or four sub-points that provide relevant examples, diagrams, and equations.
2. Refer to the Starting Points questions on page 58. Answer these questions using what you have learned in this chapter. How have your answers changed?
3. Design a one-page graphic organizer that describes each of the following:
   - how to solve the different types of projectile motion problems
   - how to add vectors by scale diagram in two dimensions

Vocabulary

resultant vector (p. 61)

component vector (p. 68)

projectile (p. 76)

projectile motion (p. 76)

time of flight (p. 76)

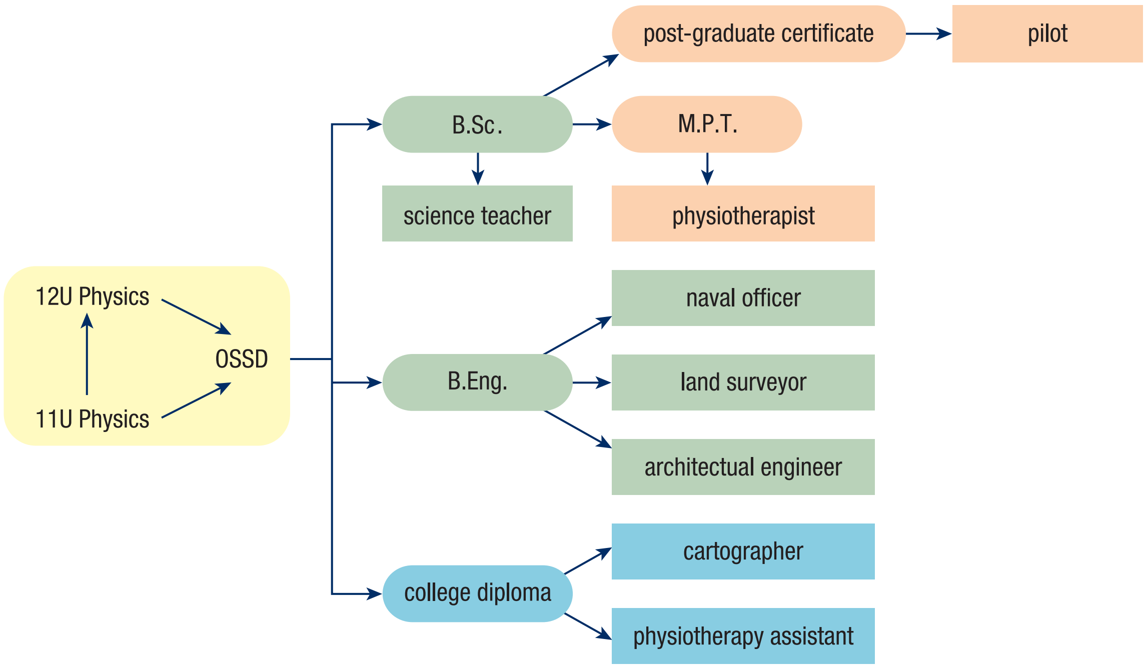
range (p. 76)

CAREER **PATHWAYS**

SKILLS HANDBOOK A7

Grade 11 Physics can lead to a wide range of careers. Some require a college diploma or a B.Sc. degree. Others require specialized or post-graduate degrees. This graphic organizer shows a few pathways to careers related to topics covered in this chapter.

1. Select an interesting career that relates to Motion in Two Dimensions. Research the educational pathway you would need to follow to pursue this career. What is involved in the required educational programs? Summarize your findings in a brief report.
2. What is involved in becoming a cartographer? Which educational programs would you need to complete to pursue this career, and in what fields do cartographers work? Research at least two programs and share your findings with a classmate.


post-graduate certificate
pilot
B.Sc.
M.P.T.
science teacher
physiotherapist
12U Physics
OSSD
11U Physics
naval officer
B.Eng.
land surveyor
architectural engineer
cartographer
college diploma
physiotherapy assistant

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CHAPTER 2 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. Which vector direction is equivalent to E 58° S? (2.1) K/U
   - (a) W 58° N
   - (b) S 32° E
   - (c) E 32° S
   - (d) N 32° W
2. For a diagram scale of 1 cm : 50 m, what is the real-world measurement of a 3.2 cm diagram measurement? (2.1) T/I
   - (a) 160 m
   - (b) 160 cm
   - (c) 320 m
   - (d) 32 m
3. How long would a displacement of 430 m be drawn on a scale diagram of 1 cm : 75 m? (2.1) T/I
   - (a) 5.7 m
   - (b) 57 cm
   - (c) 5.7 cm
   - (d) 0.57 km
4. What is the *y*-component of the displacement vector $\Delta\vec{d}_T = 74.0$ m [S 68.0° W]? (2.2) T/I
   - (a) 27.7 m [W]
   - (b) 27.7 m [S]
   - (c) 68.6 m [W]
   - (d) 68.6 m [S]
5. An ocean liner travels a distance of 750 km [N] before turning and travelling 370 km [W]. What is the total magnitude of displacement of the ocean liner? (2.2) T/I
   - (a) 840 km
   - (b) 1120 km
   - (c) 380 km
   - (d) 980 km
6. Which of the following terms describes an object that moves in response to gravity along a two-dimensional curved trajectory? (2.3) K/U
   - (a) trajectory
   - (b) free-body
   - (c) projectile
   - (d) falling body
7. What is the time of flight for a projectile that has an initial speed of 23 m/s and is launched from the ground at 57° from the horizontal? (2.3) T/I
   - (a) 2.6 s
   - (b) 1.9 s
   - (c) 4.2 s
   - (d) 3.9 s
8. Galileo found that the distance falling bodies travel is related to the square of time by doing what? (2.4) K/U
   - (a) dropping balls from buildings
   - (b) rolling balls down ramps
   - (c) throwing stones into the air
   - (d) watching stones sink in water
9. Which of the following best describes an accelerometer? (2.5) K/U
   - (a) a tiny device made of superconducting material that causes objects to accelerate
   - (b) a tiny device made of semiconducting material that measures acceleration
   - (c) a tiny device that uses resistors to measure the acceleration of gravity
   - (d) a device that uses crystals to accelerate electric circuits and saves energy

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

10. The average velocity of a boat crossing a river is increased by the current when the motor of the boat is perpendicular to the current. (2.2) K/U
11. A diagram with a scale of 1 cm : 1 nm could be used to represent something small, such as a cell or a molecule. (2.1) K/U
12. To find the direction of the vector 30 m [N 22° W], point west and then turn 22° north. (2.1) K/U
13. The horizontal component of a vector using the cardinal directions is the component of that vector that points north or south. (2.2) K/U
14. The magnitude of a vector with components 4.0 m [W] and 7.0 m [S] is 11 m. (2.1) K/U
15. The direction of the resultant vector with components 5.2 m/s [S] and 8.5 m/s [E] is [S 31° E]. (2.2) K/U
16. The vector 57.0 m [S 22° E] has an *x*-component of 21.4 m [W]. (2.2) K/U

To do an online self-quiz,

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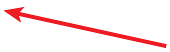
CHAPTER 2 REVIEW

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

Knowledge

For each question, select the best answer from the four alternatives.

1. Which of the following terms is used to describe the vector that is generated when adding two vectors? (2.1) K/U
   (a) compass vector
   (b) resultant vector
   (c) diagonal vector
   (d) general vector
2. Which vector direction is equivalent to N 40° W? (2.1) K/U
   (a) N 50° W
   (b) N 50° E
   (c) E 50° N
   (d) W 50° N
3. For a diagram scale of 1 cm : 10 m, what is the real-world measurement of a 2.5 cm diagram measurement? (2.1) K/U
   (a) 2.5 m
   (b) 25 m
   (c) 25 cm
   (d) 250 m
4. What distance does the vector in **Figure 1** represent in real life? (2.1) K/U



scale 1 cm : 50 m

Figure 1

   (a) 110 m
   (b) 110 cm
   (c) 2.2 m
   (d) 2.2 km
5. What is the x-component of the displacement vector $\Delta\vec{d}_T = 24$ m [S 22° E]? (2.2) K/U
   (a) 9.7 m [S]
   (b) 9.0 m [E]
   (c) 22 m [E]
   (d) 22 m [S]
6. A family on a road trip has to take a detour off the main highway. In doing so, they travel 27 km [N] and then turn to travel 11 km [E]. What is their displacement while on the detour? (2.2) K/U
   (a) 32 km [N 70° W]
   (b) 38 km [N 68° E]
   (c) 29 km [N 22° E]
   (d) 35 km [N 68° W]
7. A projectile is launched from the ground with an initial horizontal velocity of 5.0 m/s [right] and an initial vertical velocity of 6.5 m/s [up]. At what angle from vertical is it launched? (2.2, 2.3) T/I
   (a) 40°
   (b) 50°
   (c) 52°
   (d) 38°
8. A projectile is launched at an initial velocity of 11 m/s from the ground at 30° from the vertical. How long does it take before it reaches its maximum height? (2.3) T/I
   (a) 0.97 s
   (b) 0.56 s
   (c) 0.79 s
   (d) 1.12 s
9. Whose theories was Galileo testing when he performed his falling-body experiments? (2.4) K/U
   (a) Aristotle
   (b) Newton
   (c) Descartes
   (d) Einstein

Indicate whether each of the statements is true or false. If you think the statement is false, rewrite it to make it true.

10. A diagram with a scale of 1 cm : 10 cm means that 10 cm on the diagram represents 1 cm in real life. (2.1) K/U
11. To find the direction of the vector 5 m [E 30° S], point east and then turn 30° to the south. (2.1) K/U
12. To add two vectors on a diagram, join them tip to tip. (2.1) K/U
13. The resultant vector is the vector that results from subtracting the given vectors. (2.1) K/U
14. When given the x- and y-component vectors, the Pythagorean theorem should be used to determine the direction of the displacement vector. (2.2) K/U
15. The resultant vector of an object after travelling 10 km [N] and then 10 km [E] has a direction of [N 45° E]. (2.2) K/U
16. The x-component of the vector 8.0 m [S 45° W] is 8.0 m [W]. (2.2) K/U
17. The amount of time it takes a boat to cross a river is not affected by the current as long as the boat is pointed perpendicular to the direction of the current. (2.2) K/U
18. A beanbag that is launched horizontally will hit the ground at the same time as an identical beanbag that is dropped from the same height at the same time. (2.3) K/U

19. When two objects are dropped from the same height at the same time, the heavier object will land first when there is no air resistance. (2.3) K/U

Match each term on the left with the most appropriate description on the right.

20.

(a)	projectile motion	(i)	the horizontal distance a projectile travels
(b)	range	(ii)	the motion of an object that moves in response to gravity
(c)	time of flight	(iii)	believed that objects fall at constant speeds and that more massive objects fall faster than less massive objects
(d)	Galileo	(iv)	the time it takes a projectile to complete its motion
(e)	Aristotle	(v)	proved that all objects have the same constant acceleration in free fall

(2.1, 2.2, 2.3, 2.4) K/U

Understanding

Write a short answer to each question.

21. (a) Describe a situation in which a diagram would have a scale that is smaller than the real-world measurement. For example, 1 cm on the diagram would represent a distance larger than 1 cm in real life.
    (b) Describe a situation in which a diagram would have a scale that is larger than that of the real-world measurement. For example, 1 cm on the diagram would represent a distance smaller than 1 cm in real life. (2.1) K/U C

22. For each of the following displacement vectors, determine the vector that has the same magnitude but the opposite direction: (2.1) T/I
    (a) $\Delta\vec{d} = 17$ m [W 63° S]
    (b) $\Delta\vec{d} = 79$ cm [E 56° N]
    (c) $\Delta\vec{d} = 44$ km [S 27° E]

23. Copy and complete **Table 1** using a scale diagram of 1 cm : 50 m. (2.1) K/U

Table 1

Diagram size	Real-world size
3.4 cm	
	37.5 m
85.0 mm	
	1250 m

24. Draw the following displacement vectors to scale using the scale 1 cm : 100 m: (2.1) K/U
    (a) $\Delta\vec{d} = 210$ m [S 45° E]
    (b) $\Delta\vec{d} = 370$ m [N 60° W]
    (c) $\Delta\vec{d} = 560$ m [E 30° N]

25. For each of the following real-world distances, give an appropriate scale such that the equivalent diagram distance would be 2.4 cm. (2.1) T/I
    (a) 120 m
    (b) 360 km
    (c) 1200 m

26. Express each of the following vectors differently by using an equivalent direction: (2.1) K/U
    (a) $\Delta\vec{d} = 566$ m [W 18° N]
    (b) $\Delta\vec{d} = 37$ cm [E 68° S]
    (c) $\Delta\vec{d} = 7150$ km [S 38° W]

27. A woman is travelling home after work and drives her car 750 m due west and then turns right and travels 1050 m before stopping. Use a scale diagram to determine her net displacement. (2.1) T/I

28. A player hits the cue ball in billiards for the opening break. The cue ball initially travels 2.0 m [N], hits the billiard ball formation, and then travels a distance of 0.80 m [N 45° W]. Create a scale diagram for the cue ball, and use it to determine the net displacement. (2.1) T/I

29. Copy and complete **Table 2**, which involves component vectors and the magnitude of their resulting vector. (2.2) T/I

Table 2

d_x	d_y	d_T
3.0	4.0	
8.0		10.0
	5.00	7.81
4.00		8.06

30. Copy and complete **Table 3**, which involves the component vectors and the direction of the resulting vector. (2.2) T/I

Table 3

$\vec{d}_x$	$\vec{d}_y$	ϕ
3.0 [E]	4.0 [N]	
5.00 [W]	7.00 [N]	
82.0 [E]		E 14.4° S
	456 [N]	W 52.4° N

31. Determine the magnitude and direction of the *x*-component and *y*-component for the following displacement vectors: (2.2) K/U
    (a) $\Delta\vec{d}_{\text{T}} = 52$ m [W 72° S]
    (b) $\Delta\vec{d}_{\text{T}} = 38$ km [E 14° N]
    (c) $\Delta\vec{d}_{\text{T}} = 92$ m [S 82° W]

32. For each of the following, add the two component vectors and give the resulting displacement vector: (2.2) K/U
    (a) $\Delta\vec{d}_x = 5.0$ m [W], $\Delta\vec{d}_y = 2.9$ m [S]
    (b) $\Delta\vec{d}_x = 18$ m [E], $\Delta\vec{d}_y = 5.2$ m [N]
    (c) $\Delta\vec{d}_x = 64$ km [W], $\Delta\vec{d}_y = 31$ m [N]

33. Determine the magnitude of the vector in **Figure 2**. (2.2) K/U

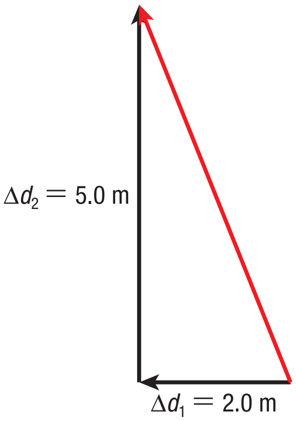


Figure 2

34. Determine the magnitude of the vector in **Figure 3**. (2.2) K/U

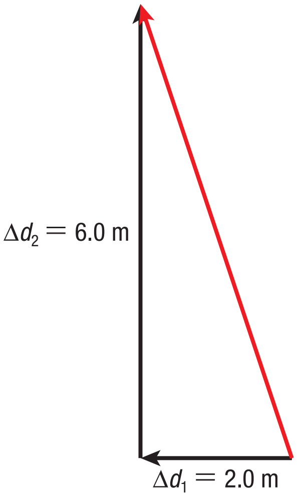


Figure 3

35. Determine the magnitude of the vector in **Figure 4**. (2.2) K/U

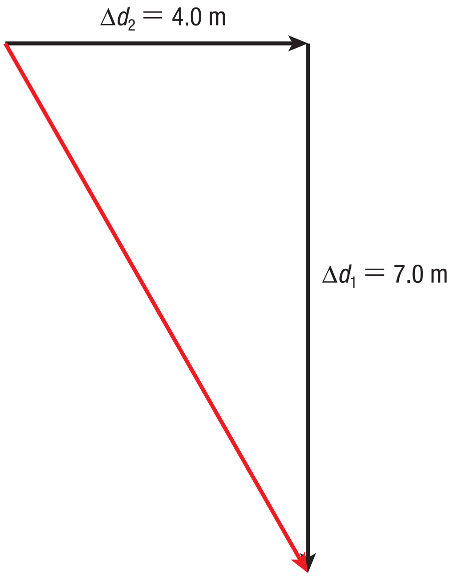


Figure 4

36. You decide to take your dog to the leash-free zone in the park. While playing, the dog runs after a ball and heads 24 m [W 12° S] and then gets distracted by a squirrel and runs 33 m [E 52° S]. Determine the displacement of the dog. (2.2) T/I

37. A student is on the southern bank of a river that is 36 m wide and has a current with a velocity of 6.2 m/s [W]. She needs to get directly across the river and decides to point the motor of the boat due north. The motor can push the boat with a speed of 2.0 m/s. (2.2) T/I
    (a) How long does it take the student to get across the river?
    (b) What is the resulting velocity of the boat?
    (c) When the student lands on the opposite bank, how far is she from her destination?

38. A student throws two beanbags in the air, one straight up and the other one at a 30° angle from the vertical. Both beanbags are thrown with the same initial velocity and from the same height. In your own words, explain which one will come back and hit the ground first and why. (2.3) C

39. During a kickball game, a student kicks the ball from the ground, giving the ball an initial velocity of 15 m/s at an angle of 50° from the horizontal. Determine the initial vertical and horizontal velocity components. (2.3) T/I

40. Students are performing an experiment for their physics class and are testing their predictions for projectile motion. They set up a system so that a beanbag is launched horizontally off one of their desks with an initial speed of 4.2 m/s. They measure the height of the desk to be 1.3 m. (2.3) T/I
    (a) What time of flight should the students predict for the beanbag?
    (b) What range should the students predict for the beanbag?

41. A historical society is testing an old cannon. They place the cannon in an open, level field and perform a few test fires to determine the speed at which the cannonballs leave the cannon. The cannon is placed at a 45.0° angle from the horizontal and placed in a bunker so that the cannonballs are fired from ground level. They measure the flight time of one cannonball to be 3.78 s. (2.3) T/I
    (a) What is the speed of the cannonball as it leaves the cannon?
    (b) What is the horizontal distance that the cannonball travels?

Analysis and Application

42. A man walking through the city travels one block (50 m) north, one block east, and then another block north. (2.1) T/I
    (a) Describe the vectors that would be used to create a diagram of his trip. Be sure to include an appropriate scale.
    (b) Create a diagram for his trip, and use it to determine the total displacement.

43. In a race, a boat travels a distance of 220 m [E 40° N] and then rounds a buoy and travels a distance of 360 m [N 30° W] to the finish line. The whole trip takes 22 s. Create a scale diagram for the boat, and use it to determine the displacement and average velocity of the boat. (2.1) T/I

44. You are told that the three vectors $\vec{a}$, $\vec{b}$, and $\vec{c}$ fit the equation $\vec{a} + \vec{b} = \vec{c}$ but you are only given scale drawings of vectors $\vec{c}$ and $\vec{a}$. (2.1) T/I C
    (a) Describe how you would place the vectors $\vec{c}$ and $\vec{a}$ on a diagram so that you could determine the size and direction of vector $\vec{b}$.
    (b) How would (a) change if you were given vectors $\vec{b}$ and $\vec{c}$ and needed to determine the magnitude and direction of vector $\vec{a}$?
    (c) Does it matter which component vector is given? That is, can either method of (a) or (b) be used no matter which component vector is given first? Explain.
    (d) Given the vectors $\vec{a} = 2.1$ cm [W] and $\vec{c} = 4.3$ cm [W 45° N], draw a scale diagram to determine vector $\vec{b}$.

Use **Figure 5** to answer Questions 45 to 50. For all questions, assume that routes must use only the roads (shown in grey).

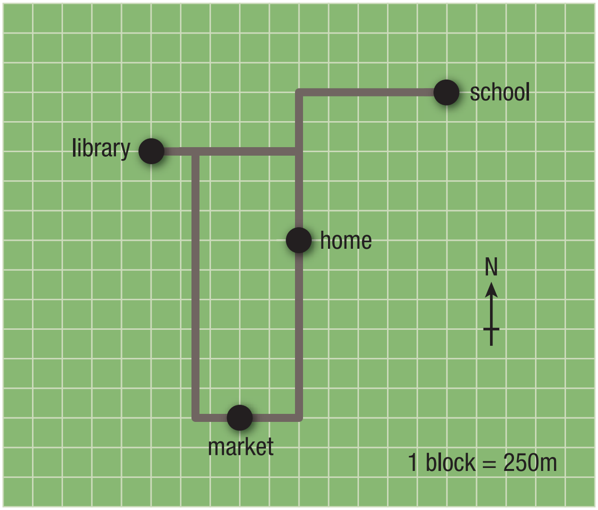


Figure 5

45. A student bikes to school every day from her home. She decides that the safest way to get there is to stay along the roads. Using vectors, describe the path she takes and determine the total distance she travels. (2.1) T/I

46. One night after studying at the library a student decides to stop at the market to pick up some dinner before going home. (2.1) T/I
    (a) Using vectors, describe the shortest path he can take while staying on the roads.
    (b) The speed limit on both of the roads is 40.0 km/h. If the student drives at this speed, how many minutes will it take him to get there?
47. A university student decides to go to the library one evening after returning home from work. What is his net displacement? (2.1) T/I
48. A Grade 12 student decides to go to the market at lunchtime from school. Determine her net displacement. (2.2) T/I
49. A mother is picking up her children from school and will take them home. She drives the speed limit of 25 km/h on each of the roads. (2.2) T/I
    (a) How many minutes does it take her to drive home from the school?
    (b) What is her average velocity from school to home?
50. After school one evening a student decides to head to the library to study for a physics test. He determines that his average speed on the trip was 25.2 km/h. How many minutes did it take him to travel from school to the library? (2.2) T/I
51. A boat travelling close to the coast is heading in an unknown direction. The captain contacts an observer on the shore to help her determine the direction the boat is heading. The observer on the shore reports that the horizontal displacement of the boat is 750 m [E] and that the boat travelled north an unknown distance. The captain has measured a total distance of 1100 m that the boat moved. How far north did the boat travel and in what direction is the boat travelling? (2.2) T/I
52. A football player trying to kick a field goal has determined that he needs to kick the ball in the direction of [N 32° W] in order to make it through the centre of the posts. If he is 13 m [E] of centre field (the field runs north to south), how far does he need to kick the ball in order to make it through the centre of the posts? (2.2) T/I
53. A hockey puck travels a distance of 11 m [N] in 0.55 s and is then hit by another player and travels a distance of 26 m [W 42° N] in 1.2 s. Calculate the average velocity of the puck. (2.2) T/I
54. An ecologist is trying to test for the average speed of a river that runs north to south, but he only has a boat and a stopwatch. He knows that the motor can push the boat with a speed of 5.2 m/s and that the width of the river is 35 m. While sitting in the boat on the eastern bank he points the motor due west. While on the western bank he has to walk a distance of 25 m to get back to the spot where he was aiming. How fast is the river current? (2.2) T/I
55. A student stands on the southern bank of a river that is 50 m wide and has a current with a velocity of 1.1 m/s [E]. The student needs to get directly across the river using her boat. (2.2) T/I C A
    (a) In order for the student to reach her destination, what must be the resulting direction of the velocity of the boat?
    (b) Describe in which direction the student should point the motor so that the net velocity of the boat is the same as the direction you determined in (a). Consider the vector components of the velocity of the boat and how they must add with the velocity of the river.
    (c) If the motor can push the boat with a speed of 3.8 m/s, what direction should the student point the motor to ensure that she reaches her destination?
    (d) How long does it take the student to cross the river?
56. Physics students are performing an experiment and slide a hockey puck off a horizontal desk that is 1.2 m high. The initial speed of the hockey puck is 1.5 m/s. (2.3) T/I
    (a) Determine the range of the hockey puck.
    (b) Determine the final velocity and angle at which it hits the ground.
57. A video game programmer is designing a soccer game and running tests to ensure that the game is as accurate as possible. As a test, a ball is kicked with an initial velocity of 16.5 m/s at an angle of 35° above horizontal. (2.3) T/I
    (a) Calculate the soccer ball's time of flight.
    (b) Calculate the soccer ball's range.
    (c) Calculate the soccer ball's maximum height.
58. The video game programmer runs another test, in which the ball has a flight time of 2.2 s, a range of 17 m, and a maximum height of 5.2 m. (2.3) T/I
    (a) What is the initial speed with which the ball is kicked?
    (b) What is the angle at which the ball is kicked?

Evaluation

59. Explain why solving motion problems in two dimensions by using scale diagrams is not very effective for most situations. (2.2) C

60. We can order events in time. For example, event *b* may precede event *c* but follow event *a*, giving us a time order of events *a*, *b*, *c*. Hence, there is a sense of time, distinguishing past, present, and future. Is time therefore a vector? Explain why or why not. (2.2) T/I

61. Two students are conducting controlled experiments to determine the relationship between the vertical displacement of a projectile and the projectile's time of flight and range. Student A launches her projectile from three different heights and records the horizontal displacement for each launch. Student B launches her projectile from three different heights, but repeats the launch and records the horizontal displacement 10 times for each of the three heights. (2.3) T/I
    (a) What variables are being manipulated in this experiment? What variables are being controlled?
    (b) Which student's data will be the most valid? Explain your reasoning.
    (c) What are some possible sources of error in this experiment? What could the students do to minimize error?

Reflect on Your Learning

62. Use what you have learned about drawing vectors to answer the following questions: K/U C
    (a) Describe in your own words how two vectors should be drawn when added together and how to determine the resultant vector.
    (b) Using the methods you have learned, describe how you would subtract two vectors.
    (c) Which method of vector addition do you prefer, using scale diagrams or breaking vectors down to components? Why?

63. In this chapter, you have learned how to solve some types of motion problems. What questions do you still have about solving motion problems? How could you find out more about solving motion problems? K/U C

Research

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64. The compass rose (**Figure 6**) has been used for centuries by sailors and navigators alike. Research the compass rose, and write a few paragraphs describing its origin, development, and how it came to be the prominent symbol for direction and navigation. C A

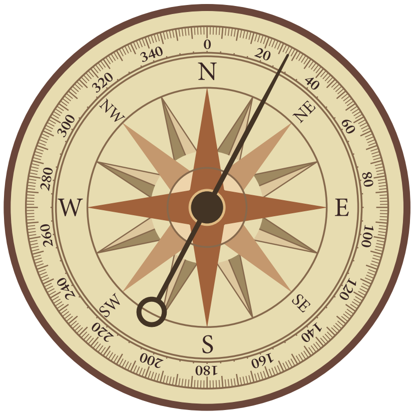


Figure 6

65. The Cartesian coordinate system, which is widely used today not only for plotting vectors but also for graphing equations and geometric problem solving, was developed around the same time Galileo performed his legendary falling bodies experiment. The coordinate system largely contributed to Galileo's and Newton's quest to accurately define the motion of objects. Research the Cartesian coordinate system. Write a paper about the history of the Cartesian coordinate system and how it helped shape our modern understanding of mathematics and physics. Include information about other coordinate systems that are used and how they differ from the standard two-dimensional grid. C A

66. In Section 2.5, you did some research about accelerometers and how they are used in many of the technological devices in our daily life. Aside from technology, accelerometers are also used to study nature, especially in the areas of seismic activity and animal motion. Research some of the ways accelerometers are used to help study nature and write a one-page report on your findings. C A

67. Electronic speed devices are used to measure the speed of objects for various purposes. For example, an electronic speed device may be used to measure the motion of a baseball thrown by a professional pitcher, or the motion of a car driving down the highway. Choose one of these two applications of electronic speed devices, and investigate how the electronic speed device works and how its use affects either the game of baseball or highway safety. T/I A

Legendary Legume Launcher

You will design and construct a launcher that will launch beanbags at a target placed on the ground at a variety of known distances (**Figure 1**). Your objective is to minimize the total distances off target for three launches. To do this, you will first need to calibrate your launcher carefully over a set of test launches at targets at distances of 8 m, 10 m, and 12 m.

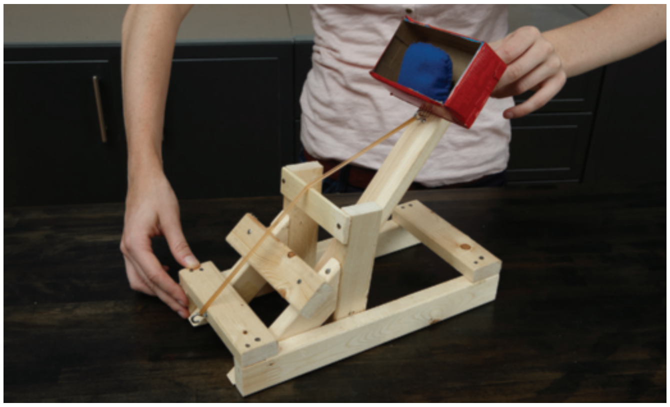


Figure 1

Purpose

To design and construct a beanbag launcher and calibrate it to fire beanbags accurately at various target distances

Equipment and Materials

Select the equipment and materials you will need to construct, test, and calibrate your beanbag launcher. Include a list of these parts with the written description of your design. Be sure to include any necessary safety equipment, such as eye protection.

Design

Prepare three labelled diagrams of your launcher, drawn to scale, and a written description of your design. The diagrams may be drawn on computer or by hand, and should include a left side view, top view, and front view. Your teacher will approve your design before you begin construction.

Consider the following when designing your launcher:

- How will your launcher be powered?
- How will your device launch a beanbag and successfully accomplish the assigned task?
- How will you ensure that your launcher is mechanically sound, environmentally friendly, and safe?
- How will you calibrate your launcher for various distances?
- How will you trigger your launcher?
- What will you do to ensure you fill your beanbags consistently?
- What will you do to make your launcher easy to transport, store, set up, and fire?
- What modifications are you considering for this project?
- Is there anything else about your project that you feel your teacher should know?
- Your launcher must be deemed to be completely safe by your teacher; otherwise, launches will not be allowed.
- Your launcher is to be no larger than 1.0 m^3 before launch and must be self-contained: it must not include a remote control or any wires, strings, or levers extending from it.
- The force propelling the beanbag must be mechanical. That is, human force may only be used to set the machine prior to launch. No explosives or compressed gases are to be used.
- Include a complete parts list for your project, specifying measurements and materials for each part.

Procedure

1. Construct your beanbag. Beanbags must be made of non-rigid material and must be between 5.0 cm and 7.0 cm in diameter. Your teacher will check the size of the beanbag before it is launched. Dried beans in the beanbag must be in the same natural state as when purchased. No additives are allowed.
2. Construct your launcher according to your approved design.

3. Complete trials to calibrate your launcher for distances of 8 m, 10 m, and 12 m by making test launches at each of these distances and adjusting the settings of your launcher. The target is a coloured pie plate 15 cm in diameter.
4. Present your calibration data in the form of a data table or graph.
5. For the final trial, launch three beanbags at each target. Only launches based on calibration data are allowed. Measure the distance from the centre of the target to where the beanbag hits the ground for each launch. If a beanbag breaks during a launch, you may relaunch.

No launches are to take place without teacher approval and supervision. You must indicate to your teacher when you are ready to launch, and you must receive teacher permission before launching your beanbag. Ensure no one is in front of the launcher. You must operate your launcher safely at all times. Eye protection must be worn at all times.

6. Record your final score as the sum of the three distances off target. The lower the sum, the better your launcher's performance.

Analyze and Evaluate

(a) Describe what you did to adjust your launcher for the different calibration distances. C

(b) Based on your understanding of projectile motion, explain why the adjustments you described in Question (a) were effective. T/I C

(c) For the final trial, explain how you determined the correct setup for your launcher. C

Apply and Extend

(d) Discuss the environmental impact of your launcher and beanbag, and explain how you could reduce the negative environmental impact of your design. C A

(e) Discuss changes you could make, either to your setup or to your design, to reduce the sum of your distances off target in your final trials. C A

ASSESSMENT **CHECKLIST**

Your completed Unit Task will be assessed according to the following criteria:

Knowledge/Understanding

- ✓ Demonstrate knowledge and understanding of the characteristics of projectile motion.
- ✓ Demonstrate knowledge and understanding of the relationship between the horizontal and vertical components of a moving projectile.

Thinking/Investigation

- ✓ Develop a plan for constructing an effective beanbag launcher.
- ✓ Construct and safely operate a beanbag launcher.
- ✓ Incorporate environmental considerations into the design and construction of a beanbag launcher.
- ✓ Analyze launch results.
- ✓ Collect calibration data for a beanbag launcher.
- ✓ Evaluate and modify your beanbag launcher design.

Communication

- ✓ Communicate to your peers how your beanbag launcher operates, has been modified, and has been calibrated.
- ✓ Communicate to your peers the materials used.
- ✓ Communicate in a clear and concise way.
- ✓ Use appropriate terminology related to kinematics.

Application

- ✓ Alter a number of design variables to modify the projectile's motion.
- ✓ Successfully achieve the goal of this Unit Task.
- ✓ Build a mechanically sound, environmentally friendly, and safe beanbag launcher.

UNIT 1 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. The term *kinematics* is best described as
   (a) a term used to quantify motion
   (b) the study of position
   (c) the study of how objects move
   (d) a term used to quantify inertia (1.1) K/U
2. Suppose you attach a string to the beginning of a winding path and walk to the end. There, you pull the string straight and measure its length. What would you be measuring? (1.1) K/U
   (a) displacement
   (b) distance
   (c) direction
   (d) position
3. You walk 27 m [W] and 12 m [E]. What is the total distance you have travelled? (1.1) K/U
   (a) 29 m
   (b) 15 m
   (c) 39 m
   (d) 25 m
4. Which of the following involves only a scalar? (1.1) K/U
   (a) A fish swims 20 m [E].
   (b) A truck accelerates at 8 m/s^2.
   (c) A bus driver drives 30 km/h [N].
   (d) A giraffe runs 10 m [S].
5. A cyclist travels 36 km in 3.0 h. What is her speed in metres per second? (1.2) T/I
   (a) 3.0 m/s
   (b) 3.3 m/s
   (c) 5.2 m/s
   (d) 12 m/s
6. For a straight line on a position–time graph, the rise refers to the change in which quantity? (1.2) T/I
   (a) slope
   (b) time
   (c) velocity
   (d) position
7. The slope of a position–time graph measures which of the following quantities? (1.2) K/U
   (a) average acceleration
   (b) instantaneous velocity
   (c) average velocity
   (d) distance
8. For the position–time graph of an object moving in one dimension, which of the following properties would imply that the object has motion with non-uniform velocity? (1.2) K/U
   (a) The graph is a straight line with a slope of 3.
   (b) The graph is a curve.
   (c) The graph is a horizontal line.
   (d) The graph is a negative line.
9. An object accelerates at a rate of 1.2 m/s^2 [W] for 2.0 s and has an initial velocity of 5.0 m/s [E]. What is its final velocity? (1.3) T/I
   (a) 1.4 m/s [E]
   (b) 2.6 m/s [E]
   (c) 6.2 m/s [W]
   (d) 7.4 m/s [W]
10. If you were to find the area under a velocity–time graph, which of the following quantities would you be calculating? (1.5) K/U
    (a) displacement
    (b) instantaneous velocity
    (c) average acceleration
    (d) time
11. Which of the following directions is equivalent to [E 31.7° S]? (2.1) K/U
    (a) [E 31.7° N]
    (b) [S 58.3° E]
    (c) [S 68.3° E]
    (d) [S 31.7° W]
12. How long would a distance of 625 m be if represented on a scale diagram with a scale of 1 cm : 125 m? (2.1) T/I
    (a) 5.0 cm
    (b) 4.5 cm
    (c) 4.0 cm
    (d) 3.5 cm
13. If you are standing next to a wall that runs east and west, and move a displacement of $\Delta\vec{d} = 25$ m [E 63° S], approximately how far away from the wall would you be? (2.2) T/I
    (a) 11 m
    (b) 16 m
    (c) 22 m
    (d) 25 m [E]

14. A plane has to steer off course to go around a large storm. In doing so it travels 60.0 km [N] and 75 km [E]. What is the displacement of the plane after travelling off course? (2.2) T/I
    (a) 135 km [N 41° E]
    (b) 121 km [S 51° E]
    (c) 112 km [N 59° E]
    (d) 96 km [N 51° E]
15. A river has a current of 2.3 m/s. A man points his boat so that it is directed straight across the river. In still water the boat can move with a speed of 3.2 m/s. What is the average speed of the boat while travelling across the river? (2.2) T/I
    (a) 1.1 m/s
    (b) 2.8 m/s
    (c) 3.9 m/s
    (d) 5.5 m/s
16. A projectile is launched with an initial velocity of 42 m/s at an angle of 70° with the horizontal. What is its initial vertical velocity? (2.2, 2.3) T/I
    (a) 49 m/s [up]
    (b) 39 m/s [up]
    (c) 24 m/s [up]
    (d) 14 m/s [up]
17. A basketball is shot with an initial velocity of 16 m/s at an angle of 55°. What is the approximate horizontal distance that the ball travels in 1.5 s? (2.2, 2.3) T/I
    (a) 9.1 m
    (b) 13 m
    (c) 14 m
    (d) 20 m
18. Whom did Albert Einstein consider to be the father of modern science? (2.4) K/U
    (a) Aristotle
    (b) Newton
    (c) Galileo
    (d) Descartes

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

19. If your position is 20 m [W] and you change the reference point to a location that is 20 m [E] of the previous reference point, then your new position is 0 m. (1.1) K/U
20. The terms *vector* and *scalar* both refer to quantities that have magnitude and direction. (1.1) K/U
21. Vector scale diagrams show the vectors associated with a displacement, drawn to a particular scale. (1.1) K/U
22. If a squirrel runs 5.0 m [S] and then runs 7.0 m [N], then the displacement of the squirrel is 2.0 m [S]. (1.1) T/I
23. If you measure the total distance that an object travels and divide this by the time it took to travel, then you will get the average velocity. (1.2) K/U
24. An object in motion that changes direction can have uniform velocity. (1.2) K/U
25. To find the acceleration of an object, you calculate the slope of the velocity–time graph. (1.3) K/U
26. A girl riding a bike who accelerates at a rate of 0.8 m/s^2 for 3.0 s will have a final velocity of 3.5 m/s [forward] if she starts with an initial velocity of 1.1 m/s [forward]. (1.3) T/I
27. When comparing two velocity–time graphs, the one with the steeper slope will have a smaller acceleration. (1.4) K/U
28. When an object reaches terminal velocity, it will fall at a constant acceleration. (1.6) K/U
29. According to Transport Canada, fuel consumption could drop by as much as 50 % if drivers reduced their speed on the highway from 120 km/h to 100 km/h. (1.7) K/U
30. A diagram depicting a human tissue cell could reasonably have a diagram scale of 1 nm : 1 cm. (2.1) K/U
31. The direction of the vector 5 m [E 41° S] has the same direction as the vector 2 m [S 49° E]. (2.1) K/U
32. The resultant vector is determined by taking the difference between two vectors. (2.1) K/U
33. When you are given two component vectors and you want to determine the angle of the resultant vector, you should use the inverse cosine function. (2.2) K/U
34. A vector with components of 11 m [E] and 20 m [S] has a direction of S 61° E. (2.2) T/I
35. A vector that has a magnitude of 8.9 m and an *x*-component of 5.2 m has a *y*-component of 3.7 m. (2.2) K/U
36. Computing the component vectors of a projectile can be done separately because the two components are independent of one another. (2.3) K/U
37. The time of flight for a projectile that is dropped from a height of 3.0 m is 0.61 s. (2.3) T/I
38. Galileo studied the motion of objects by rolling balls down inclined planes and noting the time it took each ball to travel the given distance. (2.4) K/U
39. Tiny accelerometers that can measure the tilt and position of a device are used in cellphones and gaming devices. (2.5) K/U

Knowledge

For each question, select the best answer from the four alternatives.

1. What is your displacement if you walk 50 m east and then 15 m west? (1.1) K/U
   (a) 75 m west
   (b) 65 m west
   (c) 35 m east
   (d) 65 m east
2. Which of the following situations most accurately demonstrates an object moving with uniform velocity? (1.2) K/U
   (a) a bungee jumper
   (b) a dribbling basketball
   (c) a sailboat in a steady wind
   (d) the Moon orbiting Earth
3. What is the average speed of a jaguar that runs 252 m in 40.0 s? (1.2) T/I
   (a) 5.95 m/s
   (b) 6.30 m/s
   (c) 6.75 m/s
   (d) 7.12 m/s
4. Which of the following formulas would you use to calculate acceleration? (1.3) K/U
   (a) $\dfrac{\Delta\vec{d}}{\Delta t}$
   (b) $\dfrac{\Delta t}{\Delta\vec{v}}$
   (c) $\dfrac{\Delta\vec{d}}{\Delta\vec{v}}$
   (d) $\dfrac{\Delta\vec{v}}{\Delta t}$
5. A girl drops a penny off a bridge. The penny lands in the water after 1.2 s. What is the speed of the penny just before it hits the water? (1.6) T/I
   (a) 10 m/s
   (b) 12 m/s
   (c) 13 m/s
   (d) 14 m/s
6. Speed limiters are devices that
   (a) monitor the speed of cars during inclement weather
   (b) are put on the road to slow cars above a certain speed
   (c) are put in cars to electronically limit teen drivers to a maximum speed
   (d) monitor the overall traffic patterns for a city and set speed limits accordingly (1.7) K/U
7. For a diagram scale of 1 cm : 25 km, what is the actual distance represented by a 3.0 cm diagram measurement? (2.1) T/I
   (a) 0.75 km
   (b) 3.0 km
   (c) 25 km
   (d) 75 km
8. What is the *x*-component of the displacement vector $\Delta\vec{d}_T$ = 36.0 m [S 38° E]? (2.2) T/I
   (a) 11.4 m [E]
   (b) 22.2 m [E]
   (c) 28.5 m [E]
   (d) 34.4 m [E]
9. Four students travelling to a sporting event make a mistake with their directions and end up travelling out of their way. They are able to use a map to get themselves back on track, but their mistake caused them to travel 15 km [N] and then 5.3 km [W]. What displacement resulted from their wrong directions? (2.2) T/I
   (a) 22 km [N 18° W]
   (b) 20 km [W 16° N]
   (c) 18 km [N 74° W]
   (d) 16 km [N 16° W]
10. A rocket is launched from the ground with an initial horizontal velocity of 4.8 m/s [right] and an initial vertical velocity of 9.5 m/s [up]. At what angle from the horizontal is it launched? (2.2, 2.3) T/I
    (a) 72°
    (b) 63°
    (c) 39°
    (d) 27°

11. Before Galileo performed his experiments with falling bodies, which one of Aristotle's theories was considered to be true? (2.4) K/U
    (a) All objects fall at the same constant rate no matter their size.
    (b) Objects fall at a constant rate, with heavier objects falling more quickly than lighter objects.
    (c) All objects accelerate at the same rate when falling.
    (d) Smaller objects fall more quickly than larger objects.

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

12. Motion is the change in location of an object, as measured by an observer. (1.1) K/U
13. If a person walks 25 m [E] and then walks 10 m [W], then the total distance travelled by the person is 35 m. (1.1) K/U
14. The average velocity of an object is the change in time divided by the change in displacement. (1.2) K/U
15. An object with non-uniform velocity is either changing speed or changing direction or both. (1.2) K/U
16. A runner that is veering left to pass another runner is not accelerating. (1.3) K/U
17. Since 1987, the annual number of automobile accident fatalities in Canada has increased by 33 %. (1.7) K/U
18. A diagram where 150 m in real life is represented as 1 cm on the diagram has a scale of 150 m : 1 cm. (2.1) K/U
19. When given only the *x*-component and *y*-component vectors, trigonometric ratios should be used to determine the magnitude of the displacement vector. (2.2) K/U
20. The resultant vector after travelling 12 km [S] and then 19 km [W] has a direction of W 32° S. (2.2) K/U
21. Vertical and horizontal motions are independent of each other, but they do share the common factor of time. (2.2) K/U
22. If a bowling ball and a feather are dropped at the same time from the same height in a vacuum, then the bowling ball will hit the ground first. (2.3, 2.4) K/U
23. Galileo showed that the distance that falling bodies travelled is proportional to the square of the time measured. (2.4) K/U

Match each term on the left with the most appropriate description on the right.

24. (a)	displacement	(i)	where the velocity of an object changes at a constant rate
(b)	resultant vector	(ii)	a device that measures acceleration
(c)	velocity	(iii)	a graph describing the motion of an object with position on the vertical axis
(d)	accelerometers	(iv)	the vector given after adding vectors
(e)	position–time graph	(v)	an object's total displacement divided by the total time taken for the motion
(f)	motion with uniform acceleration	(vi)	a vector along the direction of a coordinate axis
(g)	component vector	(vii)	the change in position of an object (2.3, 2.5) K/U

Write a short answer to each question.

25. In your own words, describe what position is. Use your description to explain the difference between displacement and distance. Provide an example. (1.1) K/U
26. (a) What is the difference between a scalar and a vector?
    (b) Describe how vectors are drawn and how two vectors are added on a diagram. (1.1) K/U
27. Name one reason for and one reason against requiring speed limiters for teenage drivers. (1.7) K/U

Understanding

Use Figure 1 to answer Questions 28 to 30.

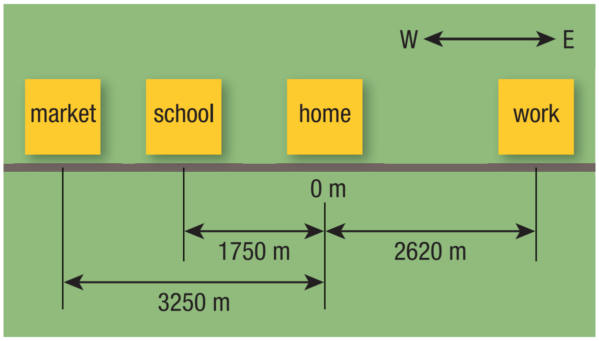


Figure 1

28. Your mom asks you to go to the market after school to pick up some milk. What is your displacement from school when you are at the market? (1.1) T/I
29. After work one day you go to the market to pick up a few things. What is your displacement? (1.1) T/I
30. A girl gets sick in school. Her dad stops at the market first to get medicine, and then picks her up and takes her home. What is the displacement of the girl? (1.1) T/I
31. A bird flying between trees changes its position from 121 m [W] of a flagpole to 64 m [E]. What is the displacement of the bird? (1.1) T/I
32. During a straightaway, a race car travels a distance of 280 m in 4.3 s. What is the average speed of the race car on the straightaway? (1.2) K/U
33. A bird is hunting for food and flies 420 m [E] from its nest in 14.4 s. What is the average velocity of the bird during its flight? (1.2) T/I
34. A car travels from 32 km [W] of a railroad to 27 km [E] of the railroad in 1.8 h. What is the velocity of the car in metres per second? (1.2) T/I
35. A racing team is testing a new design for a car. The car is able to pass through a straight portion of track in 13.7 s when its average speed is 263 km/h. How long is that portion of the track? (1.2) T/I
36. (a) An object moves according to the position–time graph given in **Figure 2**. Does the object have uniform velocity? Explain.
    (b) From the graph, determine whether the object's velocity is positive or negative and how it is changing. (1.2) K/U

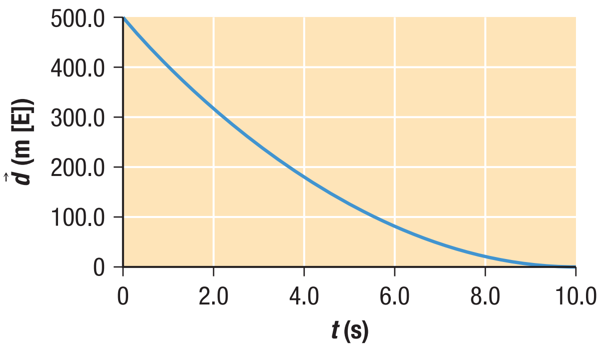


Figure 2

37. (a) Explain the difference between average velocity and instantaneous velocity. Is it possible for these two values to be different?
    (b) Given a position–time graph, describe how you would determine average velocity and instantaneous velocity. (1.2, 1.3) K/U C
38. A runner leaves from his home, and in 1.6 s his speed is 2.8 m/s. Determine the acceleration of the runner. (1.3) T/I
39. A race horse starts running once the gates fall and accelerates at a rate of 7.10 m/s^2 for 2.20 s. What is the final speed of the horse? (1.3) T/I
40. An arrow is shot from a crossbow. How long will it take the arrow to accelerate from rest to a speed of 152 m/s if the crossbow can accelerate the arrow at a rate of 1.35×10^4 m/s^2? (1.3) T/I
41. **Figure 3** is a velocity–time graph for an object under constant acceleration. Determine the displacement of the object over the interval 0 s to 4.0 s. (1.4, 1.5) T/I

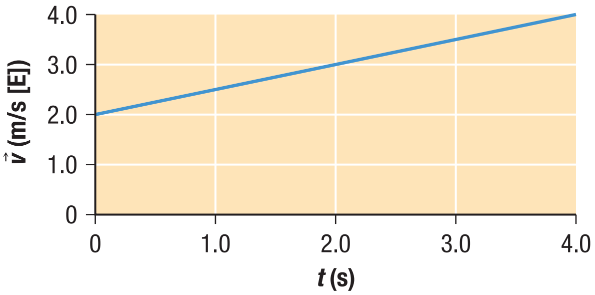


Figure 3

42. To test the durability of a new shock-proof camera, the company has the camera dropped from a height of 15.0 m. Assume air resistance is negligible. (1.6) T/I
   (a) How long does it take for the camera to hit the ground?
   (b) What is the speed of the camera just before it hits the ground?

43. Draw each displacement vector to scale using the scale 1 cm : 100 m. (2.1) K/U
   (a) $\Delta\vec{d} = 710$ m [S 45° E]
   (b) $\Delta\vec{d} = 280$ m [N 20° E]
   (c) $\Delta\vec{d} = 530$ m [W 70° N]

44. Express each vector differently by using an equivalent direction. (2.1) K/U
   (a) $\Delta\vec{d} = 86$ m [E 8° N]
   (b) $\Delta\vec{d} = 97$ cm [E 23° S]
   (c) $\Delta\vec{d} = 3190$ km [S 68° W]

45. A high school student is travelling home after work. She drives her car 850 m due west and then turns right and travels 1150 m before stopping. Use a scale diagram to determine her net displacement. (2.1) T/I

46. The cue ball in billiards is hit for the opening break. It initially travels 2.1 m [N] and then hits the rack of balls and travels a distance of 0.91 m [N 63° E]. Create a scale diagram for the cue ball, and use this to determine the net displacement. (2.1) T/I

47. Copy **Table 1**. Use the given values to solve for and fill in the missing component vectors and magnitudes of the resulting vectors. (2.2) T/I

Table 1

$\vec{d}_x =$	$\vec{d}_y =$	$\vec{d}_T =$
6	8	
5.0		13
	15	17
2.0		7.3
6.0	6.7	

48. Copy **Table 2**. Use the given values to solve for and fill in the missing component vectors and the direction of the resulting vectors. (2.2) T/I

Table 2

$\vec{d}_x =$	$\vec{d}_y =$	ϕ
5.0 [E]	12.0 [N]	
15.00 [W]	8.00 [N]	
91.0 [E]		[E 58.9° S]
	213 [N]	[W 18.4° N]
0.051 [W]		[W 63° S]

49. Determine the magnitude and direction of the x-component and y-component for each displacement vector. (2.2) K/U
   (a) $\Delta\vec{d}_T = 82$ m [W 76° S]
   (b) $\Delta\vec{d}_T = 34$ m [E 13° N]
   (c) $\Delta\vec{d}_T = 97$ m [S 65° W]

50. For each of the following, add the two component vectors and give the resulting displacement vector: (2.2) K/U
   (a) $\Delta\vec{d}_x = 4.0$ m [W], $\Delta\vec{d}_y = 1.9$ m [S]
   (b) $\Delta\vec{d}_x = 1.9$ m [E], $\Delta\vec{d}_y = 7.6$ m [N]
   (c) $\Delta\vec{d}_x = 72$ m [W], $\Delta\vec{d}_y = 15$ m [N]

51. Three children are throwing a disc in the park. The first child throws the disc 32 m [W 14° S] to the second child, who then throws the disc 15 m [E 62° S]. What is the net displacement of the disc? (2.2) T/I

52. A fish is at the western bank of a river that is 64 m wide and has a current with a velocity of 0.90 m/s [S]. The fish swims directly across the river going due east. The fish can swim at a speed of 0.2 m/s. (2.2) T/I
   (a) How long does it take the fish to get across the river?
   (b) What is the resulting velocity of the fish?
   (c) When the fish arrives on the opposite bank, how far is it from being at the point directly across from where it started?

53. A student drops one pen out a window. At the same time, he throws another pen horizontally with a velocity of 10 m/s. Which pen will hit the ground first? Explain. (2.3) K/U C

54. In a children's soccer game, one of the children kicks the ball from the ground, giving it an initial velocity of 22 m/s at an angle of 62° to the horizontal. Determine the initial vertical and horizontal velocity components. (2.3) T/I

55. A tennis ball machine (**Figure 4**) launches balls horizontally with an initial speed of 5.3 m/s, from a height of 1.2 m. (2.3) T/I

Figure 4

(a) What will the time of flight be for a tennis ball launched by the ball machine?
(b) What will the range of the tennis ball be? (2.3)

Analysis and Application

56. A roller coaster is climbing up a hill on the track at a vertical velocity of 0.60 m/s when it reaches the top and begins to accelerate down the opposite side of the hill. 5.50 s after the roller coaster starts going down the hill, it has a vertical velocity of 27.0 m/s downward. What is the average vertical acceleration of the roller coaster over this portion of the track? (1.3) A

57. Use **Figure 5** to answer the following questions: (1.3) T/I A
    (a) Determine the average acceleration over the time interval 0 s to 3.0 s.
    (b) Determine the average acceleration over the time interval 2.0 s to 6.0 s.
    (c) Determine the total displacement over the time interval 0 s to 6.0 s.

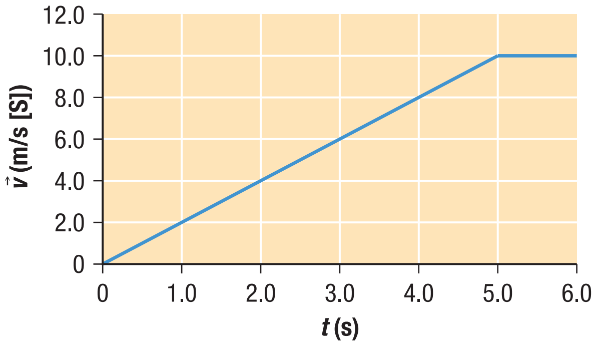


Figure 5

58. Compare the two velocity–time graphs in **Figure 6**. Which one has the greatest acceleration in magnitude? In your own words, explain how you can determine this. (1.3) T/I

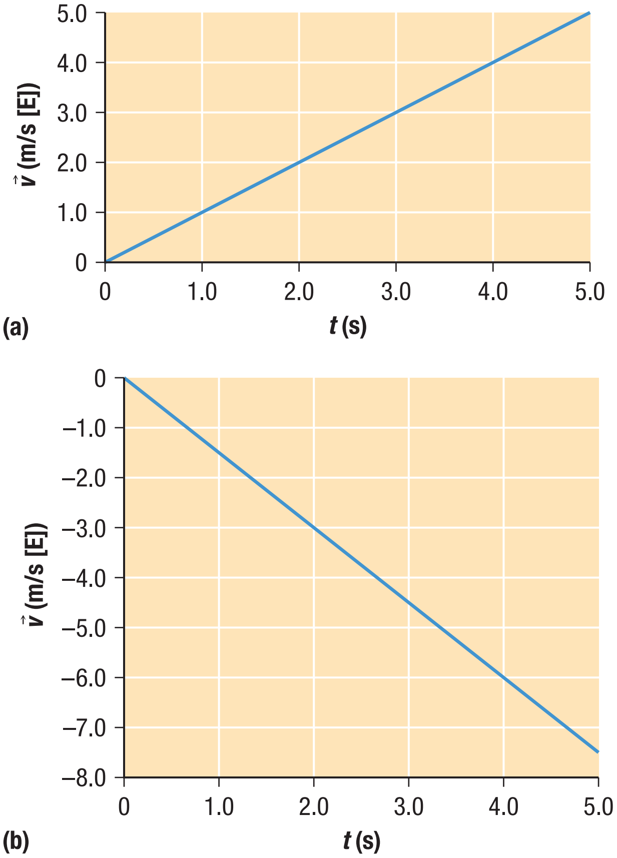


Figure 6

59. Describe what each position-time graph would look like given the initial conditions. Draw a rough sketch for each graph described. (1.4) K/U C
    (a) An object has a constant positive acceleration and starts from rest at a zero position reference point.
    (b) An object has a constant positive acceleration but initially has a negative velocity and starts at a zero reference point.
    (c) An object has a constant negative acceleration but starts with a positive velocity and a positive distance from a given reference point.
    (d) An object has zero acceleration, a negative initial velocity, and a positive starting position from a given reference point.

60. A person is driving unsafely on the highway at a speed of 145 km/h and has to slam on his brakes in order to avoid a collision. The brakes can slow down the car at a rate of 10.4 m/s^2. (1.5) T/I
    (a) From the second the car starts to slow down, how long will it take to stop?
    (b) How far will the car travel while slowing down?

61. (a) How far does a vehicle travel if it has an initial speed of 54.0 km/h and accelerates at a rate of 1.90 m/s^2 for 7.50 s?
    (b) What would the final speed of the vehicle in (a) be? (1.5) T/I

62. The five key equations of accelerated motion have a broad range of applications and serve as the basis for understanding kinematics. Copy **Table 3** into your notebook and fill in the missing spaces by describing in what type of situation each equation is useful or what type of problem it can be used to solve. (1.5) K/U C

Table 3

	Equation	Uses
Equation 1	$\Delta\vec{d} = \left(\frac{\vec{v}_1 + \vec{v}_2}{2}\right)\Delta t$	
Equation 2	$\vec{v}_f = \vec{v}_i + \vec{a}\Delta t$	
Equation 3	$\Delta\vec{d} = \vec{v}_i\Delta t + \frac{1}{2}\vec{a}_{av}\Delta t^2$	
Equation 4	$\vec{v}_f^2 = \vec{v}_i^2 + 2\vec{a}_{av}\Delta\vec{d}$	
Equation 5	$\Delta\vec{d} = \vec{v}_f\Delta t - \frac{1}{2}\vec{a}_{av}\Delta t^2$	

63. A family takes a trip to a beach on Lake Ontario to ride jet skis. The daughter travels a displacement of 240 m [W 11° N] while passing a small island and then turns and travels 330 m [N 20° E]. This takes her 22 s. Create a scale diagram for the daughter and use it to determine her displacement and average velocity. (2.1) T/I

64. In this unit, you learned how to add two vectors by drawing them on a diagram and joining them tip to tail. In your own words, describe how this method can be adapted to subtract two vectors. (2.1) K/U C

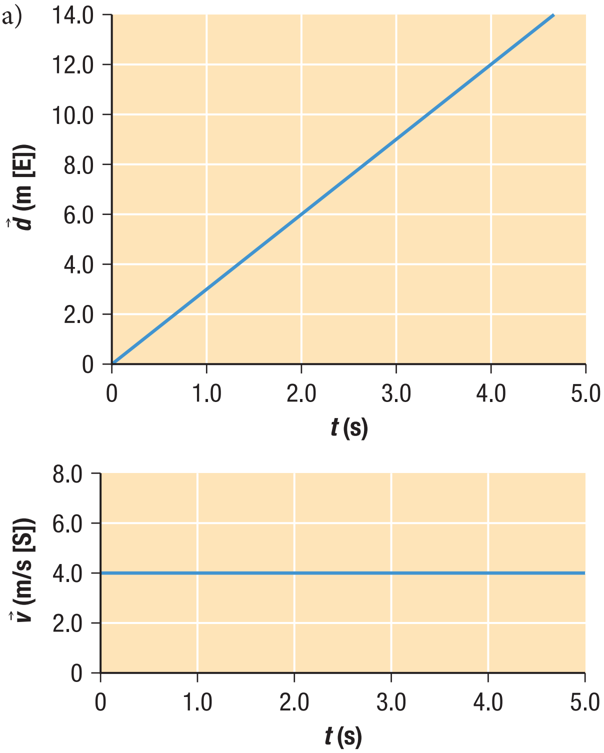
65. (a) Vectors have been used throughout this unit to quantify and give direction to real-world motions. Explain in your own words different ways in which vectors are added together for both one and two dimensions.
    (b) How do these methods compare? Try to think of ways in which the methods are similar and ways in which they are different. (1.1, 2.1, 2.2) K/U C

66. A ranger hiking through the woods is trying to determine the direction in which he's travelling. He walks in a roughly northeastern direction for a total distance of 1550 m and uses known landmarks in the distance to determine that he has travelled 1250 m [E]. How far north did he travel and what is his resulting direction? (2.2) T/I

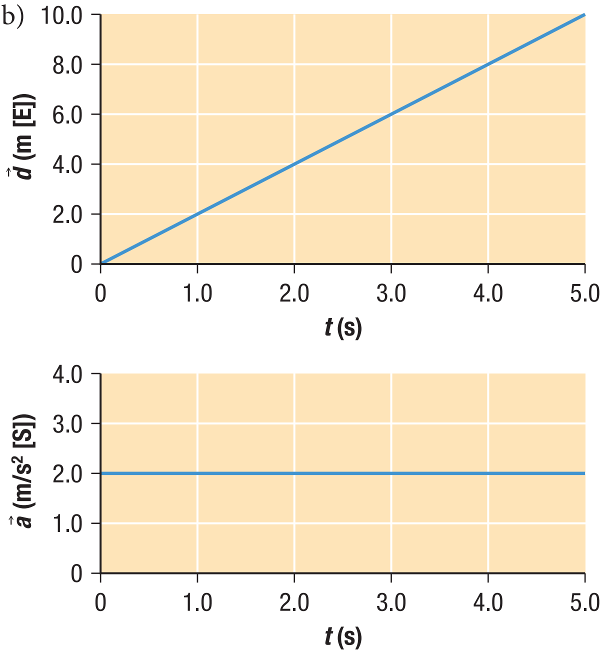
67. An archer is practising on a training course and moves a distance 11 m [E] of her original position, which is due south of her target. She is now firing in a direction of N 28° W. How far is she from her target? (2.2) T/I

68. The same position–time, velocity–time, and acceleration–time graphs you studied in Chapter 1 can also be applied in two dimensions as long as two graphs are given for each component direction. For the following graphs, determine the magnitude and direction of the velocity of an object at time $t = 3.0$ s. If you are finding the velocity from an acceleration–time graph, assume that the initial velocity in that direction is zero. (2.2) T/I A

(a)



(b)



69. (a) During the opening kickoff of a college football game, the kicker kicks a football with an initial velocity of 27.5 m/s at an angle of 41° above horizontal. What is the time of flight for the ball? How far does it travel before hitting the ground? What is the maximum height the football reaches?
    (b) After scoring, the kicker makes a mistake when kicking to the other team and kicks the ball too high. The ball stays in the air for 3.2 s and has a range of only 29 m. Determine the initial speed and angle with which the ball was kicked. (2.3) T/I

70. When studying kinematics, the topic of gravitation and projectile motion is unavoidable. Use the knowledge you have gained from Chapters 1 and 2 to answer the following questions about the motion of objects under gravitational acceleration. (2.3) T/I C A
    (a) If two objects are dropped from the same height, but one is on the Moon and the other here on Earth, which would hit the ground first?
    (b) If a beanbag is launched horizontally and another beanbag with the same mass is dropped straight down from the same height, which would hit the ground first? If this experiment were performed on the Moon, would the results be any different? Explain.
    (c) For the horizontally launched beanbag in (b), which beanbag would have the larger range, the one on Earth or the one on the Moon? Explain.

71. In astronaut training it is possible to experience an effectively gravity-free environment in an airplane that is flown in a parabolic path (**Figure 7**). Use your knowledge of projectile motion to explain this experience. (2.3) T/I A

Figure 7

Evaluation

72. In this unit, you learned how to add vectors in one and two dimensions, and in many ways the addition of vectors is the same for both one- and two-dimensional problems. Use the knowledge you gained in this unit to answer the following questions about the properties vectors should have in three dimensions. (1.1, 2.1) T/I C A
    (a) How would drawing a vector in three dimensions be different?
    (b) If you drew a three-dimensional vector diagram to add two vectors, how would it be done and what would the resultant vector be?
    (c) How many component vectors would each three-dimensional vector have? If these were used on a three-dimensional map or image, what directions would they correspond to?
73. Did Galileo's experiments lead to the discovery of modern kinematics? Using what you have learned in Chapters 1 and 2, evaluate the impact Galileo's experiments had on the scientific community. Do you think Newton would have come up with his laws and performed his own experiments without the work of Galileo? Explain. (2.4) T/I
74. Use what you have learned about accelerometers to describe one way in which they could be added to a daily device you use. This should be a device that does not already include accelerometers, but could benefit from this added technology. What could the accelerometer be used for and what would it measure? How would the accelerometer improve your chosen device? (2.5) T/I C A

Reflect on Your Learning

75. (a) Was there any material in this unit that you found particularly illuminating in understanding how objects move?
    (b) Did you realize how useful trigonometry was for real-world applications of direction and projectiles or was this a new concept for you? C
76. How has your understanding of gravity changed after this unit? Do you feel that you have a better understanding of why objects fall and travel the way they do? If you could time travel back to the sixteenth or seventeenth century, do you think you could explain these rules to the scientists of that day? C

Research

GO TO NELSON SCIENCE

77. One of the most important uses for the science of kinematics is transportation. One of the fastest growing technologies is high-speed rails, like the one shown in **Figure 8**. Research this topic and write a few paragraphs on how this transportation method works and how it is used around the world. Predict how common you think this technology will be in the future. In later chapters, you will learn how many of these trains are able to reach such great speeds without the use of wheels. T/I C

Figure 8

78. Pick your favourite sport and research the world record speeds or distances involved. This may include the fastest slapshot in hockey, the fastest baseball pitch, the farthest-hit ball, or the fastest tennis serve. Get in groups of two or three and pick one of your sports and records. Try to reproduce the world record and take measurements on how your values compare to the record. You might have to take distance and time measurements and then perform the required calculations to come up with your values. T/I C
79. One of the biggest achievements in the twentieth century was landing on the Moon; one of the biggest ambitions we still have is to be able to make this travel accessible to everyone and expand the limits of our travel abilities. Research new topics in space travel technologies and write a paper on your favourite findings. This could include ideas about how we could travel between the Earth and space stations or ideas about how we might one day be able to travel to distant galaxies. T/I C

UNIT 2

Forces

OVERALL EXPECTATIONS

- analyze and propose improvements to technologies that apply concepts related to dynamics and Newton's laws, and assess the technologies' social and environmental impact
- investigate, in qualitative and quantitative terms, net force, acceleration, and mass, and solve related problems
- demonstrate an understanding of the relationship between changes in velocity and unbalanced forces in one dimension

BIG IDEAS

- Forces can change the motion of an object.
- Applications of Newton's laws of motion have led to technological developments that affect society and the environment.

UNIT TASK **PREVIEW**

The challenge in the Unit Task is to simulate a crash test by placing an egg at the front of a dynamics cart and smashing the cart into a wall without breaking the egg. To protect the egg, you will build a bumper to minimize the forces acting on the egg. The Unit Task is described in detail on page 204. As you work through the unit, look for Unit Task Bookmarks to see how information in the section relates to the Unit Task.

FOCUS ON **STSE**

FORCES AND TECHNOLOGY

People use their cars almost every day to get to work or school, or just to get around. Many of us take automotive technology for granted and assume that the car we are driving is safe and reliable. Yet there are many different types of cars, and the technology and safety features in them are quite different. In this unit, you will learn how forces apply to automotive and many other types of technology.

Racing cars are very different from the average family car. If you were to examine the tires on Formula One cars, you would see several differences between these types of tires and the typical all-season tire used on passenger cars. Why are racing tires wider with no treads? Why do tires on passenger cars have treads? What is the difference between an all-season tire and a snow tire? The design of the racing car is also quite different. For example, the engine in a Formula One car is far more powerful than the engine in a passenger car. How do these factors help a racing car win a race? Why are these design features not used in passenger cars?

It is important for you to become familiar with and learn how to use the many safety features of cars before learning to drive. In this unit, you will learn about these safety features and how engineers use their understanding of forces to design them. Some safety features of a car are the headrest at the back of each seat, the seat belts, and the airbags. Did you know that many people put their headrest at the incorrect height? Did you know that older-style seat belts actually caused injuries? How do airbags work?

Automotive technology is not the only type of technology involving forces. For example, why is it so easy to slide across ice and wet floors? What is near-frictionless carbon, and where might it be used? How are forces involved with sports such as snowboarding, golf, and hockey?

There are far too many applications of technology in the world to be covered in just one unit. However, you will learn enough about forces in this unit so that you can notice how forces apply to new technologies on your own. In fact, maybe you will take what you have learned about forces and discover some new application as an engineer or a scientist.

Questions

1. Identify at least one type of technology that uses forces. In what way are forces involved with the technology?
2. What forces are involved when a car accelerates from rest? How do the mass of the car and the type of tire affect the acceleration of the car?

UNIT 2 ARE YOU READY?

CONCEPTS

- motion
- velocity
- acceleration
- forces

SKILLS

- drawing and interpreting graphs
- finding the slope of a straight-line graph
- identifying linear and reciprocal relationships on graphs
- conducting investigations
- communicating scientific information clearly and accurately

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Concepts Review

1. **Figure 1** shows the motion of a car along a straight road. The images are taken at equal time intervals. Describe the motion of the car using your vocabulary of motion. C

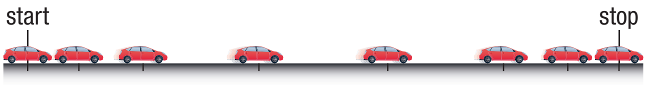


Figure 1

2. Solve each of the following kinematics problems using one or more equations of motion. T/I
   (a) Calculate the acceleration of a runner who starts from rest and reaches a final velocity of 9.6 m/s [E] in 6.0 s.
   (b) A ball is dropped from rest and falls 3.2 m before striking the ground. What is the velocity of the ball the moment before it strikes the ground?
   (c) A car moving at 32 km/h [N] accelerates for 8.2 s to a velocity of 65 km/h [N]. Calculate the average acceleration of the car.
   (d) A skater reaches a final velocity of 7.4 m/s [W] after skating for 4.0 s and moving 42 m [W]. Calculate the acceleration and the initial velocity of the skater.
3. (a) What is a force?
   (b) Describe as many different types of forces as you can. Give one example of an object experiencing each type of force. K/U C
4. Use the terms "displacement," "velocity," "acceleration," and "direction" to describe the linear motion of an object moving with
   (a) uniform motion
   (b) accelerated motion, where the object is speeding up
   (c) accelerated motion, where the object is slowing down K/U C
5. Examine the velocity–time graph in **Figure 2**. K/U T/I

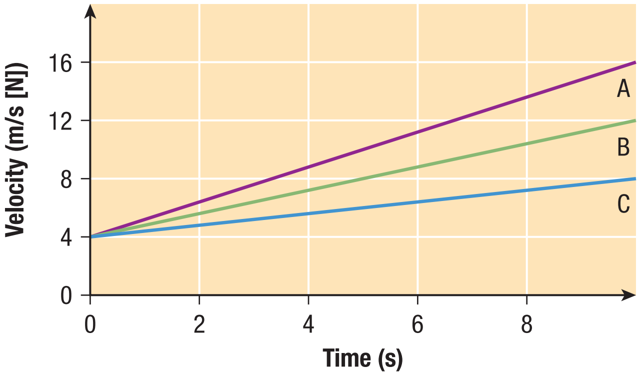


Figure 2

   (a) How can you tell that the acceleration of each object is uniform but the velocity is not uniform?
   (b) Calculate the acceleration of each object.
   (c) Which object travelled the greatest distance? Explain your reasoning.

6. You drop a golf ball, a heavy brass weight, and a paper coffee filter from a height of 2.0 m. A motion sensor is used to graph the motion of each object as it falls to the floor (**Figure 3**). K/U T/I

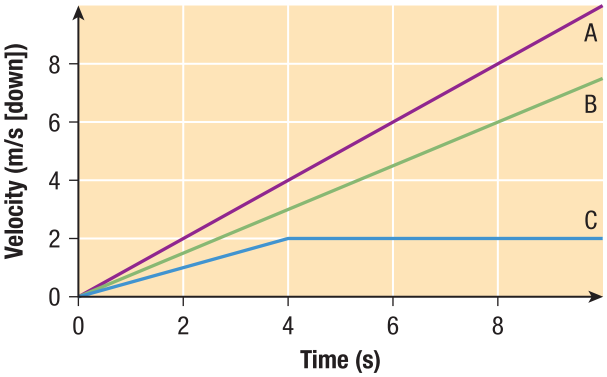


Figure 3

(a) Which line on the graph best represents the motion of each object as it falls toward the ground? Explain your reasoning.
(b) Why is the acceleration of the coffee filter different from the acceleration of the other objects?
(c) Are the accelerations of the golf ball and the brass weight significantly different? Explain your reasoning.

Skills Review

7. **Figure 4** shows three different ticker tapes representing the motion of three different objects. T/I

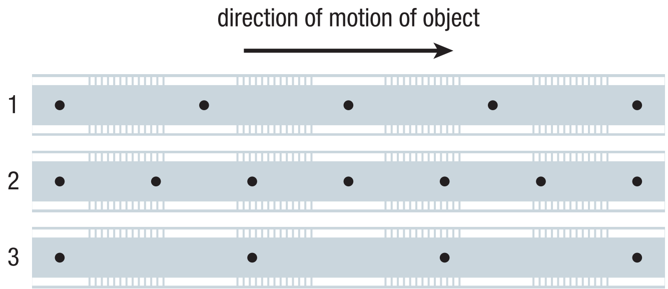


Figure 4

(a) What type of motion is represented by each ticker tape? Explain your reasoning.
(b) Which tape represents the greatest velocity? Which one represents the slowest velocity? Explain your reasoning.
(c) Calculate the velocity of each object using a ruler. The time interval between the dots is $\frac{1}{60}$ s.

8. **Figure 5** shows two different ticker tapes representing the motion of two different objects. T/I C

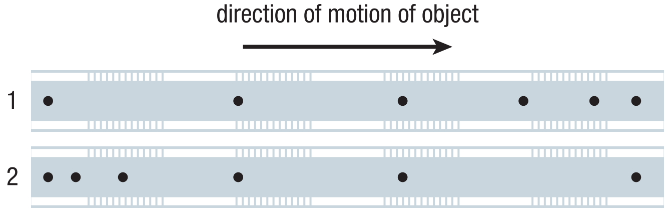


Figure 5

(a) What type of motion is represented by each ticker tape? Explain your reasoning.
(b) Sketch a reasonable velocity–time graph for the motion of each object.

9. Consider the reciprocal function $y = \frac{1}{x}$. T/I C

(a) Copy and complete **Table 1** for this function.

Table 1

x	*y*
0.5	
1	
2	
4	
10	

(b) Create a graph of the reciprocal function using your table of values. Draw a smooth curve to connect the points on the graph.
(c) Describe the shape of the graph of the reciprocal function.

CAREER PATHWAYS **PREVIEW**

Throughout this unit you will see Career Links in the margins. These links mention careers that are relevant to Forces. On the Chapter Summary page at the end of each chapter, you will find a Career Pathways feature that shows you the educational requirements of the careers. There are also some career-related questions for you to research.

CHAPTER

3 Newton's Laws of Motion

KEY CONCEPTS

After completing this chapter you will be able to

- distinguish between different types of forces and describe how they affect the velocity and acceleration of an object
- explain how Galileo and Newton advanced our knowledge of forces and motion
- state and apply Newton's laws qualitatively
- use free-body diagrams to calculate net force and acceleration
- solve problems involving forces in one dimension using free-body diagrams and Newton's laws
- conduct an inquiry into the relationship among the acceleration, net force, and mass of an object, and analyze the resulting data
- assess the environmental and social impact of technologies that involve forces

What Effect Do Forces Have on the Motion of Objects?

The skier on the opposite page has many different forces acting on him at the same time. Each force has an effect on his motion. The ground exerts forces on the skier, gravity is pulling on him, and even the air is pushing him back. When you combine all of these forces, you can determine how the skier will move. At times, the skier will move with a constant velocity, while at other times he will speed up or slow down. The sum of all the forces acting on the skier determines which of these will occur.

To help increase the speed of the skier, the skis are designed to decrease the force of friction. The skier can push on the snow-covered ground with his poles to help him speed up. Even the skier's clothing and safety equipment are designed to help increase speed and reduce drag (air resistance). An experienced skier will adjust his or her stance to reduce air resistance.

Extreme velocities are dangerous even to experienced skiers. To help reduce speed, the skier can plow through the snow or skid with his skis across the snow, causing the skis to dig into the snow.

Just reading about the physics of skiing will not make you a skilled skier, but understanding the physics behind skiing can make a good skier even better. An understanding of the physics of skiing also helps equipment designers create better skis, poles, and other skiing gear, which help skiers win races.

In this chapter, you will explore different types of forces and discover how they affect motion. You will learn Newton's three laws of motion and use them to explain how and why objects move. You will also solve problems related to forces and motion.

STARTING **POINTS**

Answer the following questions using your current knowledge. You will have an opportunity to revisit these questions later, applying concepts and skills from the chapter.

1. List as many forces as you can think of that might be acting on the skier in the photograph. For each force, give the direction of the force and suggest what might be exerting the force.
2. If the skier is moving slowly at a constant velocity across a horizontal surface, what forces do you think are acting on him? How would your answer change if the skier were moving quickly at a constant velocity?
3. What do you think is true about the direction of the total force acting on the skier if he is slowing down? What if he is speeding up?
4. What force or forces do you think would cause the skier to
   (a) speed up? (b) slow down?
5. The physics of skiing is similar to the physics of skateboarding.
   (a) List three forces that you think act on both a skier and a skateboarder.
   (b) How do you think a skateboarder can speed up and slow down?

Mini Investigation

Predicting Forces

Skills: Predicting, Performing, Observing, Analyzing, Evaluating, Communicating

SKILLS HANDBOOK A2.1

The SI unit of force is the newton. In this chapter, you will be required to measure forces using a spring scale or a force sensor. The following activity will help you improve your skills in estimating and measuring forces. Before performing this activity, make sure you know how to zero the spring scale or calibrate the force sensor.

Equipment and Materials: two spring scales or force sensors; one 100 g object; one 200 g object

1. Hang a 100 g object from a spring scale or a force sensor and record the reading.
2. Hold a 200 g object in your hand and estimate how much force is required to hold it up. Record your estimate. Hang the object from the spring scale or force sensor. Measure and record the force.
3. Predict the reading on the spring scale if you hang both the 100 g and the 200 g object from it. Record your prediction. Measure and record the force.
4. Predict the reading on each scale if you use two spring scales or two force sensors to hold up one 200 g object. Record your prediction. Test your prediction and record your results.

A. How accurate were your predictions? How could they be improved? T/I

B. What can you conclude about forces from your observations? Write one or two statements that summarize your observations. T/I C

3.1 Types of Forces

Forces are all around you, acting on every object that you see. The motion of cars, trucks, planes, and boats is determined by the forces acting on them. Engineers must consider forces carefully when designing bridges and buildings. You are always using forces to move around, to lift objects, or to turn the pages of this book. Forces are involved in every type of sport and activity. For example, when a pitcher throws a ball, she exerts a force on the ball that causes the ball to move forward (**Figure 1**). If the batter hits the ball, then the bat exerts a force on the ball to change its motion. An understanding of forces is essential for a scientific description of our environment.

Figure 1 Forces are all around you.

In simple terms, a force is a push or a pull. Forces can cause objects to change their motion. When you push on a chair to tuck it under a desk, you change the motion of the chair. The direction of a force is very important. If you push straight down on a book on a desk, the effect is usually very different than if you push sideways or pull up. This means that force has direction, making it a vector quantity.

dynamics the study of the causes of motion

In Unit 1, you studied a branch of mechanics called kinematics. Remember that kinematics is the study of how objects move without being concerned with why they move. In this unit, you will study dynamics. **Dynamics** explains why objects move the way they do. One way to understand why an object moves is to study the forces acting on it. These forces can cause the object to start moving, speed up, slow down, or remain stationary. In this chapter, you will be introduced to different types of forces and the laws that govern them.

Measuring Forces

newton (N) the SI unit of force ($1\text{ N} = 1\text{ kg}\cdot\text{m/s}^2$)

Isaac Newton discovered many of the concepts in this chapter. For this reason the unit of force, the newton, is named after him. The **newton (N)** is a derived SI unit equal to $1\text{ kg}\cdot\text{m/s}^2$.

To measure force in the laboratory, you can use either a spring scale or a force sensor. A spring scale has a spring that stretches more when greater forces pull on it. A needle is attached to the spring to indicate the amount of force. Usually a spring scale must be zeroed (the reading must be set to zero when not pulling) before use. Most spring scales can only measure a pulling force. A force sensor is an electronic device that can be attached to a computer or used independently. This device provides an accurate digital reading of a force and can even graph how the force changes over time. A force sensor can measure both pushes and pulls.

Force Diagrams

system diagram a simple sketch of all objects involved in a situation

To understand why an object will remain at rest, start moving, or change its motion, you need to be able to draw diagrams that show clearly which forces are acting on the object. These diagrams are essential, especially when several forces are acting on the object simultaneously. The first type of force diagram is called a system diagram. A **system diagram** is a simple sketch of all the objects involved in a situation. For example, if you are lifting a book up in the air, the system diagram will show your hand pulling up on the book (**Figure 2**).

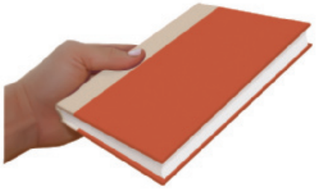


Figure 2 A system diagram is a sketch showing all the objects involved in a situation. A system diagram helps you determine which objects push or pull on other objects.

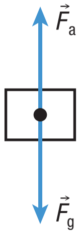


Figure 3 The FBD for the book shown in Figure 2. Since an FBD shows all the forces acting on a single object, two forces are drawn: the force of the hand pulling up and the force of gravity pulling down.

The other type of force diagram is called a **free-body diagram** (FBD). An FBD is a simple drawing representing the object being analyzed and all the forces acting on it (**Figure 3**). Usually the object is drawn as a rectangle or large dot. The forces are drawn as arrows originating from the outline of the rectangle or dot and pointing away from the centre. FBDs are not drawn to scale, but larger forces can be drawn longer than smaller ones to help predict the motion of the object. Each force is labelled with the symbol $\vec{F}$ and an appropriate subscript that indicates the type of force.

free-body diagram (FBD) a simple drawing of an object showing all the forces that are acting on it

Everyday Forces

To draw useful force diagrams, you need to be familiar with some common forces encountered every day. Imagine two children playing outside with a wagon. One child pulls forward on a rope tied to the front, while the other pushes on the wagon from behind (**Figure 4(a)**). What forces act on the wagon? To answer this question, we first need to study some everyday forces.

First consider the applied forces. An **applied force** results when one object is in contact with another object and either pushes or pulls on it. The symbol for an applied force is $\vec{F}_{\mathrm{a}}$. In our example, the child behind the wagon exerts an applied force forward on the wagon by pushing on the back. Another force is the tension force (often called tension). **Tension** is a pulling force exerted on an object by a rope or a string. The symbol for tension is $\vec{F}_{\mathrm{T}}$. Ropes and strings are not rigid, which means that they cannot push on an object. If you try to push with a rope, the rope will just sag down and have no effect on the motion of the object. An easy way to remember the direction of the tension is that it always pulls the object toward the rope or the string. The child at the front of the wagon pulls on the rope, causing tension in the rope. The rope exerts tension on the wagon, pulling it forward. Notice that in **Figure 4(b)** both the applied force vector and the tension vector start from the outline of the rectangle representing the wagon and are directed forward, indicating the direction of each force.

applied force ($\vec{F}_{\mathrm{a}}$) a force that results when one object makes contact with another and pushes or pulls on it

tension ($\vec{F}_{\mathrm{T}}$) a pulling force from a rope or string on an object that always points toward the rope or string

Whenever an object is in contact with a surface, the surface can exert two different forces on the object. One is called the normal force. The **normal force** is a perpendicular force on an object exerted by the surface with which it is in contact. The normal force is given its name because this force always acts perpendicular (or normal) to the surface. The symbol for the normal force is $\vec{F}_{\mathrm{N}}$. The normal force is always a push from the surface onto the object. For this reason, the normal force always points away from a surface. In Figure 4(b), the normal force from the ground on the wagon starts from the outline of the rectangle and points up, perpendicular to the ground. In this case, the normal force supports the wagon against the force of gravity.

normal force ($\vec{F}_{\mathrm{N}}$) a perpendicular force exerted by a surface on an object in contact with the surface; the normal force always points away from the surface

The other force exerted by a surface on an object is friction. **Friction** is a force that resists the motion or attempted motion of an object. Friction is always parallel to the surface and acts opposite to the object's motion or attempted motion. The symbol for friction is $\vec{F}_{\mathrm{f}}$. If the wagon is moving to the right, then the friction on the wagon acts toward the left, opposite to the motion. If the wagon is at rest even if the children are pushing and pulling on it, then the friction is left, opposite to the tension and applied force keeping the wagon at rest.

friction ($\vec{F}_{\mathrm{f}}$) opposes the sliding of two surfaces across one another; friction acts opposite to the motion or attempted motion

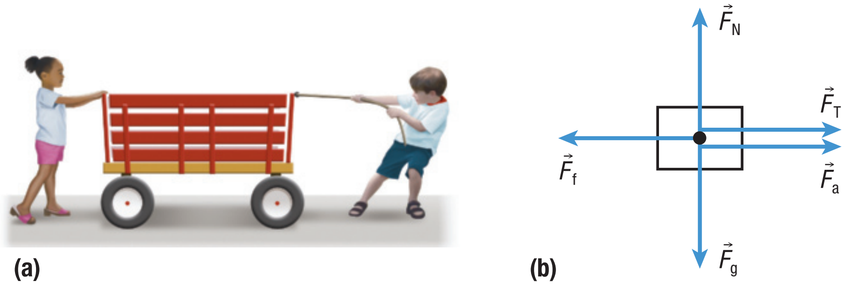


Figure 4 (a) The system diagram of a wagon and the two children pushing and pulling on it (b) The FBD showing all the forces acting on the wagon

Notice that all of the forces described on the previous page require one object to be in contact with another. For this reason, they are called contact forces. Some forces do not require contact. These forces are known as action-at-a-distance forces (sometimes called non-contact forces).

force of gravity ($\vec{F}_g$) force of attraction between any two objects

The **force of gravity**, also called the gravitational force, is the force of attraction that exists between any two objects due to their mass. The force of gravity is an action-at-a-distance force. The symbol for gravity is $\vec{F}_g$. In this course, you will only learn about the force of gravity between Earth and other objects close to Earth's surface. At Earth's surface, the force of gravity always points down toward Earth's centre. Even if the surface is sloped, such as the side of a mountain, the force of gravity still points down toward Earth's centre.

Mini **Investigation**

Measuring the Force of Gravity

Skills: Performing, Observing, Analyzing, Communicating

SKILLS HANDBOOK **A2.1, A6.5**

In this investigation, you will observe the relationship between mass and the force of gravity. You will also measure and calculate the magnitude of the force of gravity.

Equipment and Materials: spring scale or force sensor; set of objects of known mass

1. Create a table with the headings "Mass (kg)" and "Force of gravity (N)" to record your observations.
2. Select one of the objects. To measure the force of gravity on the object, hang the object from the spring scale or force sensor. Hold the object steady before taking a reading. Record your observations in your table.
3. Repeat Step 2 for all the objects in the set.

A. Graph your results with the force of gravity (N) on the *y*-axis and mass (kg) on the *x*-axis. T/I C

B. What is the slope of the line of best fit on the graph? What does the slope represent? (Hint: Think back to the projectile problems from Unit 1.) T/I C

C. Using your observations, predict the force of gravity acting on each object below. Use the spring scale or force sensor to check your predictions. How accurate were your predictions? T/I C
(i) 0.30 kg
(ii) 0.50 kg

D. Describe how you could calculate the force of gravity (N) acting on an object if you knew its mass (kg). T/I C

To calculate the magnitude of the force of gravity on an object, you multiply the mass of the object by the acceleration due to gravity. To calculate the force of gravity, you can use the equation

$$\vec{F}_g = m\vec{g}$$

where $\vec{g} = 9.8\ \text{m/s}^2$ [down]. The force of gravity is measured in newtons and the mass is in kilograms. You will learn more about gravity in Chapter 4.

In this course, you will usually be concerned with external forces. External forces are those that are caused by one object pushing or pulling on another. An internal force occurs when an object exerts a force on itself. For example, when skater A pushes on skater B, the force on skater B is external. If skater B pulls forward on her own arm, then it is an internal force.

In the following Tutorial, you will use what you have learned about forces to draw system diagrams and FBDs.

WEB **LINK**

To learn more about contact and action-at-a-distance forces,

GO TO NELSON SCIENCE

Tutorial 1 Drawing Force Diagrams

Some force diagrams are easy to draw, while others require more care. The following Sample Problems will help you to sharpen your skills with force diagrams.

Sample Problem 1

Draw both the system diagram and the FBD for each object in italics.

(a) A *cup* is sitting at rest on a table.

(b) A large *trunk* in the basement is pulled by a rope tied to the right side of the trunk by a person. The trunk does not move.

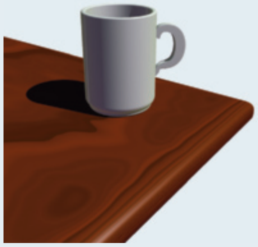
(c) A *baseball player* is sliding to the left across the ground.

(d) A *desk* is pushed to the left across the floor.

Solution

(a) **Step 1.** Identify the objects in the system diagram.

The system diagram shows the cup and also the desk because the desk exerts a force on the cup.



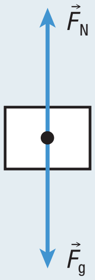
Step 2. Identify the forces acting on the cup for the FBD.

The forces acting on the cup are the normal force and gravity.

Step 3. Determine the direction of each force.

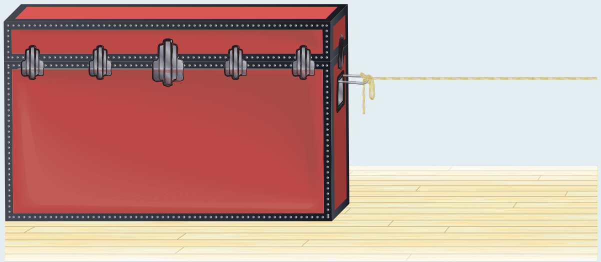
The normal force exerted by the desk pushes up on the cup and the force of gravity pulls the cup down. No one is pushing the cup so there is no applied force. There is no friction acting on the cup because the cup is not moving and friction is not required to keep it stationary.

Step 4. Draw the FBD as a rectangle representing the cup and the arrows representing each force and its direction. Each arrow must be labelled with the appropriate force symbol.



(b) **Step 1.** Identify the objects in the system diagram.

The system diagram shows the trunk, the rope, and the basement floor.



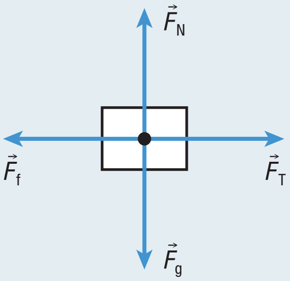
Step 2. Identify the forces acting on the trunk for the FBD.

The forces acting on the trunk are tension from the rope, the normal force, friction, and gravity.

Step 3. Determine the direction of each force.

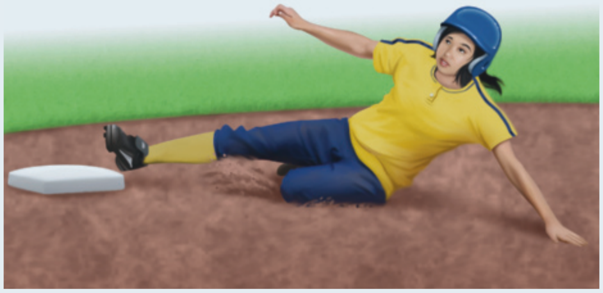
The rope can only pull, exerting tension to the right. The basement floor exerts two forces on the trunk, the normal force and friction. The normal force is perpendicular to the surface and is directed up. The force of friction acts opposite to the applied force to keep the trunk stationary. The force of gravity on the trunk is directed down.

Step 4. Draw the FBD as a rectangle representing the trunk and the arrows representing each force and its direction. Each arrow must be labelled with the appropriate force symbol.



(c) **Step 1.** Identify the objects in the system diagram.

The system diagram shows the baseball player and the ground.



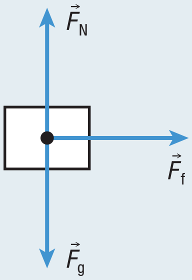
Step 2. Identify the forces acting on the baseball player for the FBD.

The forces acting on the baseball player are the normal force, friction, and gravity.

Step 3. Determine the direction of each force.

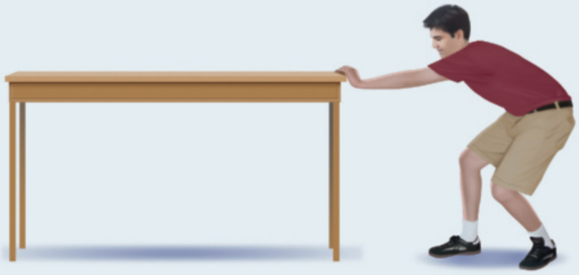
The normal force exerted by the ground pushes up on the baseball player. The force of friction is directed opposite to the direction of motion. The force of gravity pulls down on the baseball player.

Step 4. Draw the FBD as a rectangle representing the baseball player and arrows representing each force and its direction.



(d) **Step 1.** Identify the objects in the system diagram.

The system diagram shows the desk, the person pushing on it, and the floor.



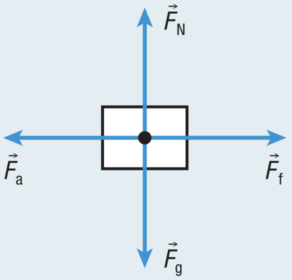
Step 2. Identify the forces acting on the desk for the FBD.

The forces acting on the desk are an applied force, the normal force, friction, and gravity.

Step 3. Determine the direction of each force.

The desk is being pushed to the left, so the applied force is directed to the left. The normal force pushes up on the desk. The force of friction is directed to the right, opposite to the direction of motion. The force of gravity pulls down on the desk.

Step 4. Draw the FBD as a rectangle representing the desk and the arrows representing each force and its direction.



Sample Problem 2

A player kicks a soccer ball that is sitting on the ground. The ball moves up into the air. Ignore air resistance.

(a) Draw the FBD of the ball after it has moved away from the player but is still in the air.

(b) A student draws the FBD shown in **Figure 5** to represent the soccer ball while it is coming back down. What is wrong with the FBD? Explain your reasoning.

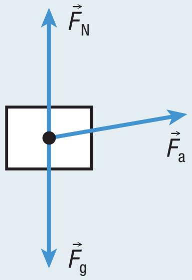


Figure 5

Solution

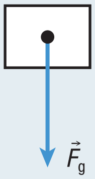
(a) **Step 1.** Identify the forces acting on the ball.

The soccer ball has moved away from the player so there is no applied force. The ball is in the air so there is no normal force exerted by the ground. The only force acting on the soccer ball is gravity.

Step 2. Determine the direction of the force.

The force of gravity pulls down on the soccer ball.

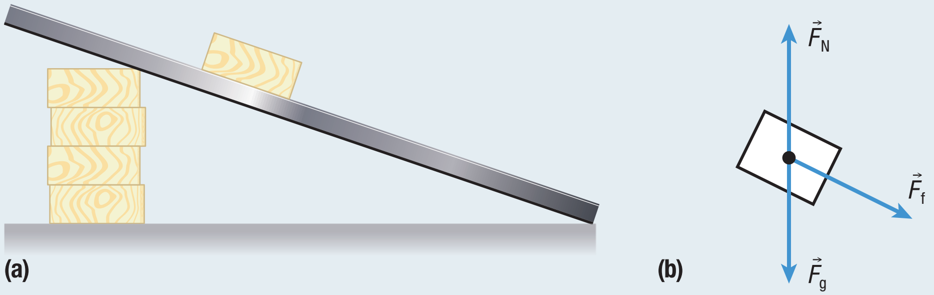
Step 3. Draw the FBD as a rectangle representing the ball and the arrows representing each force and its direction.



(b) When the soccer ball is in the air, there is no applied force or normal force. Both of these forces are contact forces. Since the ball is no longer in contact with the player's foot or the ground, these forces no longer act on the ball and should not be included in the diagram. The FBD that the student drew in Figure 5 would be appropriate at the start when the ball is still on the ground and the player is kicking it.

Practice

1. Draw a system diagram and an FBD for each object in italics. K/U C
   (a) A *book* is at rest on top of a desk.
   (b) A *basketball* falls through the hoop. Ignore air resistance.
   (c) A large *trunk* is pushed horizontally from behind toward the east across a rough floor.
2. **Figure 6(a)** shows a system diagram of a block sliding up a ramp. A student draws the FBD for the block (**Figure 6(b)**). Discuss the validity of the FBD. K/U C



(a) **(b)**

Figure 6

Calculating Net Forces

In many force problems, you must combine all the forces acting on a single object into one combined force. The total force is also called the **net force** or the resultant force. To determine the net force, you need to use FBDs. Keep in mind that force is a vector quantity and the direction of each individual force must be considered before determining the net force. Net force is represented by the symbol $\vec{F}_{net}$. In the following Tutorial, you will draw FBDs to determine the net force acting on an object.

net force ($\vec{F}_{net}$) the sum of all forces acting on an object

Tutorial 2 Using FBDs to Determine Net Force

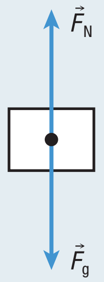
To determine the net force from the FBD of an object, it is necessary to define the *x*- and *y*-axes and to define which directions are positive. You may omit one axis or the other, if there are no forces parallel to that axis. In the following Sample Problems, we will practise this technique.

Sample Problem 1: Calculating the Net Force on a Stationary Object

The floor exerts a normal force of 36 N [up] on a stationary chair. The force of gravity on the chair is 36 N [down]. Draw the FBD of the chair and use the FBD to determine the net force on the chair.

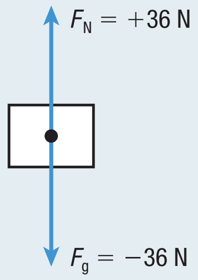
Solution

Step 1. Draw the FBD of the object.



Step 2. Identify which directions are positive.

Define up as the positive *y*-axis and down as the negative *y*-axis. This means the normal force exerted by the floor on the chair is positive and the force of gravity on the chair is negative. The values of the forces on the FBD are now



Step 3. Add the forces on each axis to determine the net force.

$$\begin{aligned}\vec{F}_{\text{net}} &= \vec{F}_{\text{N}} + \vec{F}_{\text{g}}\\ &= +36\text{ N} + (-36\text{ N})\\ F_{\text{net}} &= 0\text{ N}\end{aligned}$$

There is no net force on the chair.

Sample Problem 2: Calculating the Net Force When the FBD Is Given

Figure 7 shows all the forces acting on an object. Use the FBD to calculate the net force.

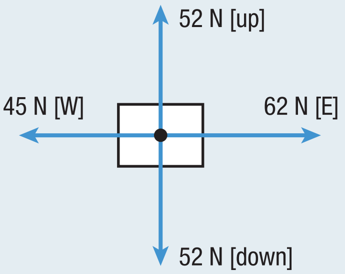


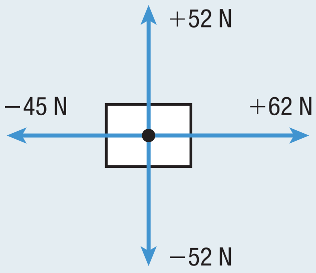
Figure 7

Solution

Since the FBD is given, you can skip the drawing step.

Step 1. Identify which directions are positive.

Choose up and east as positive. So down and west are negative. The values of the forces on the FBD are now



Step 2. Define east and west forces as being along the *x*-axis. So up and down forces are along the *y*-axis.

Add the forces along each axis to determine the net force.

First, find the sum of all the forces parallel to the *y*-axis.

$$\begin{aligned}(F_{\text{net}})_y &= +52\text{ N} + (-52\text{ N})\\ &= 0\text{ N}\end{aligned}$$

The net force on the *y*-axis is 0 N.

Now find the sum of all the forces parallel to the *x*-axis.

$$\begin{aligned}(F_{\text{net}})_x &= +62\text{ N} + (-45\text{ N})\\ &= +17\text{ N}\end{aligned}$$

The net force along the *x*-axis is 17 N [E].

Therefore, the net force on the object is 17 N [E].

Practice

1. Calculate the net force when each set of forces acts on the same object. Draw an FBD for each object. K/U C
   (a) 5.5 N [W], 3.4 N [W], 4.2 N [E] [ans: 4.7 N [W]]
   (b) 92 N [up], 35 N [down], 24 N [down] [ans: 33 N [up]]
   (c) 15 N [up], 15 N [down], 35 N [E], 12 N [W] [ans: 23 N [E]]
2. A chain exerts a force of 1200 N [up] on a beam which experiences a force of gravity of 1100 N [down]. Draw the FBD of the beam and determine the net force on the beam. K/U C [ans: 100 N [up]]
3. You push a book across a table to your friend with a force of 6.5 N [E]. The force of friction on the book is 4.5 N [W]. The normal force and the force of gravity have a magnitude of 7.5 N. Draw the FBD of the book and calculate the net force on the book. K/U C [ans: 2.0 N [E]]

The Four Fundamental Forces

It might seem like there are many different kinds of forces in everyday life and even more involved with research and technology. Physicists have grouped all known natural forces into four categories called fundamental forces. These four fundamental forces are the gravitational force, the electromagnetic force, the strong nuclear force, and the weak nuclear force.

You have already learned a little about the force of gravity, and you will expand that knowledge in Chapter 4. Not only is the force of gravity responsible for pulling objects down toward Earth's centre, but it also exists between any two masses in the universe. The force of gravity keeps the Moon in orbit around Earth and Earth in orbit around the Sun. You do not notice the force of gravity between smaller objects such as a pair of basketballs because the masses are small and the force of gravity is too weak compared to Earth's gravity.

The electromagnetic force is caused by electric charges. Electric force exists between charges, and magnetic force exists between magnets. The electromagnetic force is an action-at-a-distance force. Unlike gravity, this force can both attract and repel. For this reason, these forces often cancel each other out. The electromagnetic force holds atoms and molecules together: it makes concrete hard and a feather soft and governs the properties of chemical reactions.

In the nucleus of atoms, the positively charged protons are very close and repel each other. They do not fly apart because the strong nuclear force of attraction between the neutrons and the protons keeps them in place. In some cases, protons and neutrons can transform into other particles. The weak nuclear force is responsible for the interactions involved during these particle transformations.

Table 1 gives a brief comparison of the four fundamental forces. The electromagnetic, strong nuclear, and weak nuclear forces are studied in later physics courses.

WEB LINK

To review the four fundamental forces,

GO TO NELSON SCIENCE

Table 1 Comparing the Fundamental Forces

Type of force	Approximate relative strength	Range	Effect
gravitational	1	infinite	attract only
electromagnetic	10^{20}	infinite	attract and repel
strong nuclear	10^{38}	less than 10^{-15} m	attract and repel
weak nuclear	10^{25}	less than 10^{-18} m	attract and repel

3.1 Summary

- A force is a push or a pull. Forces are responsible for changes in motion.
- Force is a vector quantity measured in newtons (N).
- There are two types of force diagrams. A system diagram is a simple sketch of the situation showing the objects involved. A free-body diagram (FBD) shows all the forces acting on a single object.
- You can use FBDs to calculate the net force on an object. Indicate the direction of the positive y-axis and the positive x-axis to determine the signs of each force acting on the object. Add up the forces parallel to each axis to determine the net force.
- To calculate the force of gravity, you can use the equation $\vec{F}_g = m\vec{g}$, where $\vec{g} = 9.8 \text{ m/s}^2$ [down].
- The four fundamental forces are the gravitational force, the electromagnetic force, the strong nuclear force, and the weak nuclear force.

3.1 Questions

1. Assume that you are sitting at your desk facing north with a book on the desk directly in front of you. K/U
   (a) If you push on the side of the book that is closest to you, in which direction is the applied force?
   (b) If you pull on the side of the book that is closest to you, in which direction is the applied force?
2. Name the force or forces that cause these objects to experience changes in motion. Neglect air resistance. K/U
   (a) A ball falls toward the ground.
   (b) A person accelerates up in an elevator.
   (c) A car gradually slows down while approaching a red light.
3. A student forgets to zero the force sensor before performing an investigation. What effect, if any, will this have on the data collected during the investigation? T/I
4. Some everyday forces are gravity, tension, friction, an applied force, and the normal force. It is important that you be able to determine the direction of each of these forces when drawing an FBD. Create a table or a graphic organizer to help you remember the direction of these forces. K/U
5. Draw both the system diagram and the FBD for each object in italics. K/U C
   (a) A *car* is parked on the road.
   (b) A small *fish* is hanging from a fishing line.
   (c) A *football* is falling toward a player.
   (d) A *puck* is being pushed forward across the ice by a hockey stick.
6. Create a poster to teach students about common everyday forces. Include at least two system diagrams in your poster and the corresponding FBDs. You may include several everyday forces in your poster or concentrate on just one. K/U C
7. Determine the force of gravity acting on each object. T/I C
   (a) A 2.0 kg object falls straight down.
   (b) A 62 kg person stands on the floor.
8. Your teacher says, “Any applied force can also be called a normal force.” Discuss the validity of this statement. K/U C
9. You tie a long string to a cart on the ground. Explain why you can only pull the cart forward but cannot push the cart away with the string. Draw diagrams to help explain your answer. K/U C
10. Describe the main difference between contact forces and action-at-a-distance forces. What implication does this difference have when drawing an FBD? K/U C
11. Explain the difference between system diagrams and FBDs. Describe why both are used to solve force problems. K/U C
12. For a physics project, you are given a small block of wood, a paper clip, some masking tape, a balloon, a magnet, and an elastic band. The objective is to move the block from one end of a long hallway to the other in the least amount of time using only the materials listed, without touching the wood directly. Draw a system diagram showing how you would complete the task. Draw an FBD of the block of wood. Include a brief description of what you would do. T/I C
13. Examine **Figure 8**, showing a spider in a web. The web is currently under construction and consists of only a few fine strands. Draw the FBD of the spider. T/I C

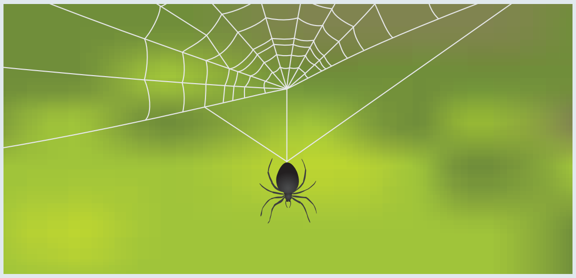


Figure 8

14. A doctor states, “The bones in the human arm can exert forces that can either push or pull other objects. The muscles are made of small fibres and can only cause tension forces.” C A
    (a) What does the doctor mean when he says muscles can only cause tension forces?
    (b) Why can bones both push and pull whereas muscles cannot?
15. Calculate the net force when each set of forces acts on a single object. T/I
    (a) 56 N [up], 35 N [down]
    (b) 12.3 N [right], 14.4 N [right], 32.7 N [left]
    (c) 45 N [up], 45 N [down], 21 N [W], 21 N [E]
16. (a) List the four fundamental forces from weakest to strongest.
    (b) Describe two ways that gravity is different from the other three fundamental forces.
    (c) Explain why friction and tension are not fundamental forces. K/U C

Newton's First Law of Motion

Every year in Canada, there are about 160 000 car accidents. These accidents cause many injuries, and about 3000 are fatal. Many of these injuries and deaths involve motorists who are not wearing seat belts or are driving too fast. An understanding of Newton's first law will help you appreciate the importance of safety features in cars such as seat belts and airbags. **Figure 1** shows a crash test designed to help engineers test and improve the safety features of new cars. What will happen to a crash test dummy during a collision if it is not wearing a seat belt and no airbag is present? Newton's first law will help us answer this question.

Figure 1 Crash tests are designed to test and improve automotive safety.

Inertia

If you have ever played air hockey, you may know that a small plastic puck moves with close to uniform velocity after you hit it. In other words, there is very little friction acting on the puck to slow it down. In fact, the net force on the puck is zero because the upward force on the puck exerted by the air and the downward force of gravity cancel each other and there is almost no friction. If you do not hit the puck at all, it will just sit there at rest if the air table is level.

Unfortunately, early scientists and philosophers did not have access to air hockey tables. They noticed that moving objects would spontaneously slow down for no apparent reason. They did not know about friction and incorrectly attributed the decrease in velocity to "lazy" objects. They concluded that a constant net force was needed to keep an object moving. They thought that larger net forces made things move at a higher constant velocity and smaller net forces made them move at a lower constant velocity. If no net force was acting on the object, they thought that the object would stop.

It was not until the 1600s that Galileo was able to perform experiments to help clear up these misconceptions. To help explain the results of his experiments, Galileo used the following thought experiment (**Figure 2**). **Figure 2(a)** shows a ball rolling down an incline, onto a horizontal surface, and up another incline. Galileo reasoned that if there was no friction acting on the ball, it would continue to roll up the second incline until it reached the same height as its starting position. If friction were present, it would not go quite as high on the second slope.

Figure 2(b) shows a situation similar to the first, but the steepness of the second incline is decreased. Galileo reasoned that the ball would have to roll farther to reach the same initial height on the second incline. In **Figure 2(c)**, the second incline has been eliminated. In this experiment, the ball will never reach the same height. Galileo concluded that if there is no friction, the ball will continue to roll forever. It will never reach the same initial height since it cannot go up another incline. We can verify Galileo's thought experiment today using equipment such as air tables, where little friction is present.

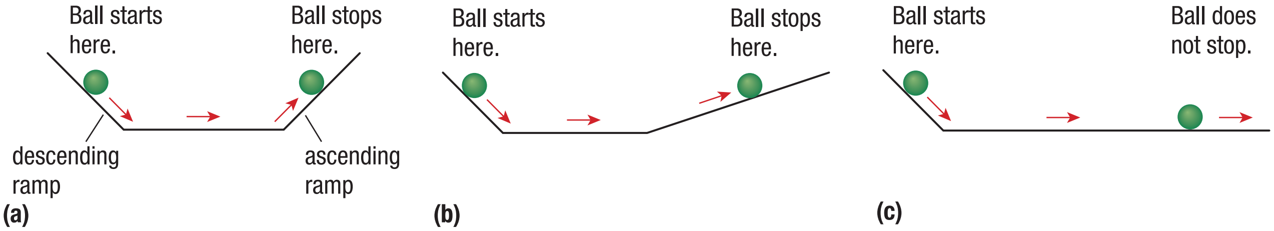


Figure 2 (a) The ball rolls up the steep second ramp until it rises to the same initial height.
(b) The ball rolls up the less steep second ramp, but it still rises to the same height.
(c) There is no second ramp and the ball never stops because it cannot get to the same initial height.

inertia the property of matter that causes it to resist changes in motion; inertia is directly proportional to the mass of the object

Galileo concluded that once an object starts moving, it will continue moving at a constant velocity if there is no friction present. Galileo used the concept of inertia to help explain his conclusion. **Inertia** is the property of matter that causes it to resist changes in motion. The inertia of an object depends on the mass of the object. An object with more mass has more inertia, whereas an object with less mass has less inertia. In other words, inertia is directly proportional to the mass of the object.

Imagine placing a stuffed animal on the dashboard of a stationary car. If the car speeds up rapidly, the stuffed animal will resist this change in motion due to its inertia and end up in your lap. This does not mean the stuffed animal is moving backwards. The car is moving forward and the stuffed animal is stationary. In other words, the dashboard is being pulled out from under the stuffed animal. If the car is moving with uniform velocity and the stuffed animal is placed on the dashboard, the stuffed animal will stay on the dashboard because there is no change in the velocity of the car. In this case, inertia does not upset the stuffed animal because inertia only resists *changes* in motion. If the stuffed animal is placed on the dashboard and the car suddenly slows down, the stuffed animal will continue to move forward with uniform velocity due to its inertia. Again, we are not implying that the stuffed animal jumps forward. It is the car that is slowing down, not the stuffed animal speeding up. The dashboard slides under the stuffed animal, causing the windshield to move toward the stuffed animal.

Newton was born in 1642, the year that Galileo died. Newton published *Principia Mathematica*, a set of three books which included much of his own work about physics, as well as a description of Galileo's law of inertia. The law of inertia is now called Newton's **first law of motion** because it was included with Newton's other laws of motion.

first law of motion an object will remain at rest or continue to move at constant velocity when the net force on the object is zero

First Law of Motion

If the net external force on an object is zero, the object will remain at rest or continue to move at a constant velocity.

Below are some of the important implications of Newton's first law:

- A non-zero net force will change the velocity of an object. The velocity can change in magnitude, direction, or both.
- A net force is not required to maintain the velocity of an object.
- External forces are required to change the motion of an object. Internal forces have no effect on the motion of an object.

Tutorial 1 FBDs and the First Law of Motion

The following Sample Problems will help to clarify the meaning of Newton's first law by using FBDs.

Sample Problem 1

Use Newton's first law to explain each situation below.

(a) Why does a computer sitting on a desk remain at rest?

(b) Why does a hockey puck moving across smooth ice move at a constant velocity?

(c) Why does a wagon pulled across a rough surface by a child move at a constant velocity?

Solution

(a) Examine the system diagram and FBD of the computer shown in **Figure 3**. Notice that the desk exerts a normal force up on the computer and the force of gravity pulls down on the computer. These two forces cancel to give a net force of zero. According to Newton's first law, the computer will remain at rest.

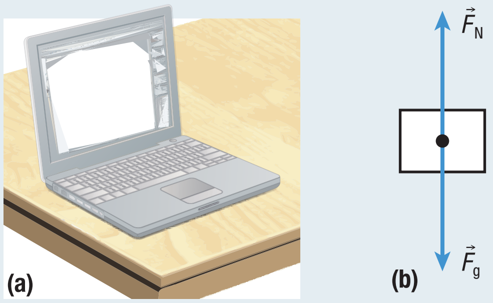


Figure 3 (a) System diagram of a computer on a desk (b) FBD of the computer

(b) Examine the system diagram and FBD of the hockey puck shown in **Figure 4**. Notice that the ice exerts a normal force up on the hockey puck and the force of gravity pulls down on the hockey puck. These two forces cancel to give a net force of zero in the vertical direction. Since no external force acts in the horizontal direction, according to Newton's first law, the hockey puck will continue to move at a constant velocity.

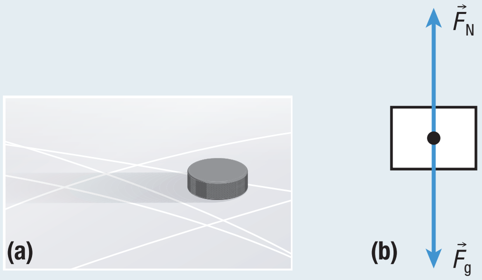


Figure 4 (a) System diagram of a hockey puck moving on ice (b) FBD of the hockey puck

(c) Examine the system diagram and FBD of the wagon shown in **Figure 5**. The child applies tension forward on the wagon. The ground exerts a normal force up, and the force of friction acts backwards on the wagon. The force of gravity acts down on the wagon. The two vertical forces cancel each other and the two horizontal forces cancel each other to produce a net force of zero. According to Newton's first law, the wagon will move at a constant velocity.

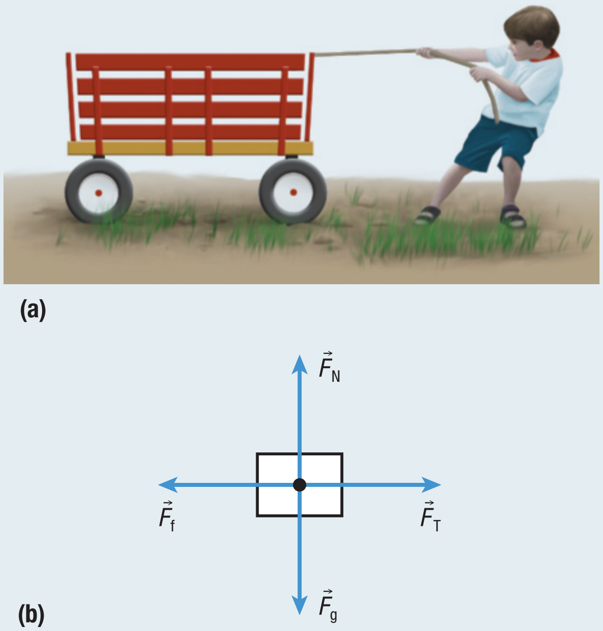


Figure 5 (a) System diagram of a child and a wagon (b) FBD of the child and the wagon

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Sample Problem 2: Newton's First Law Applied to Headrests

Older cars did not have headrests, but all new cars do. How do headrests help prevent injuries during a rear-end collision? Use Newton's first law to explain your answer.

Solution

Consider the forces acting on a person's body during a collision. During a rear-end collision, the car will suddenly accelerate forward and so will your body because the seat exerts a force directed forward on your torso. In a vintage car with no headrest (**Figure 6(a)**), there is no force applied to the head. According to Newton's first law, your head will continue to remain at rest. Your head will initially appear to snap backwards relative to your body as your body accelerates forward, possibly resulting in a neck injury known as whiplash. The headrest in a modern car helps push the head forward with the rest of the body (**Figure 6(b)**). This helps to prevent whiplash since your neck does not bend backwards as far during a rear-end collision.

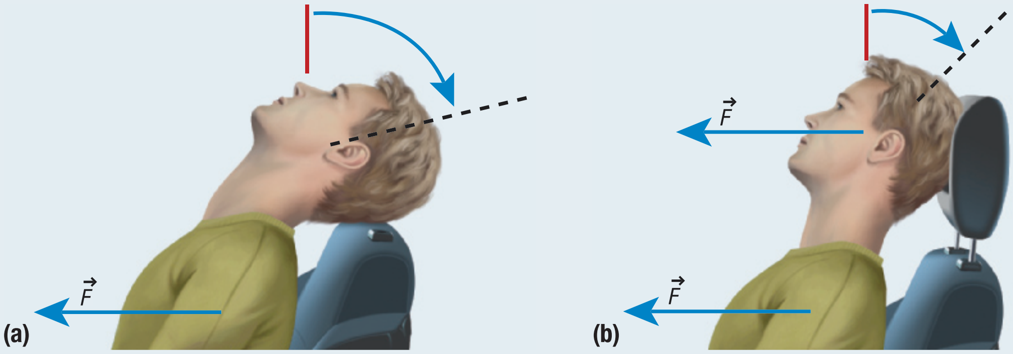


Figure 6 (a) No headrest (b) Headrest present

Sample Problem 3: Determining the Missing Force

What is the missing force on each FBD shown in **Figure 7**?

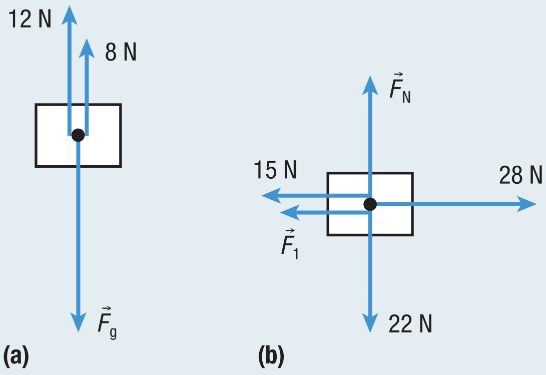


Figure 7 (a) FBD for an object at rest (b) FBD for an object moving left at a constant velocity

Solution

(a) According to Newton's first law, since the object is at rest, the net force must be zero. Choose up as positive. So down is negative.

Given: two upward forces of $+12$ N and $+8$ N

Required: $\vec{F}_g$

Analysis: $\vec{F}_{net} = 0$

Solution:
$$\begin{aligned} F_{net} &= +12\text{ N}+(+8\text{ N})+F_g \\ 0 &= 20\text{ N} + F_g \\ F_g &= -20\text{ N} \\ \vec{F}_g &= 20\text{ N}\left[\text{down}\right] \end{aligned}$$

Statement: The force of gravity on the object is 20 N [down].

(b) According to Newton's first law, the object must have a net force of zero since it is moving at a constant velocity. Choose up and right as positive. So down and left is negative. We can look at $(F_{net})y$ and $(F_{net})x$ separately. Start with the forces along the *y*-axis.

Given: -22 N

Required: $\vec{F}_N$

Analysis: $(F_{net})_y = 0$

Solution:
$$\begin{aligned} (F_{net})_y &= F_N + (-22\text{ N}) \\ 0 &= F_N - 22\text{ N} \\ F_N &= +22\text{ N} \\ \vec{F}_N &= 22\text{ N [up]} \end{aligned}$$

Now examine the forces along the *x*-axis.

Given: $+28$ N; -15 N

Required: $\vec{F}_1$

Analysis: $(F_{net})_x = 0$

Solution:
$$\begin{aligned} (F_{net})_x &= +28\text{ N} + (-15\text{ N}) + F_1 \\ 0 &= 13\text{ N} + F_1 \\ F_1 &= -13\text{ N} \\ \vec{F}_1 &= 13\text{ N [left]} \end{aligned}$$

Statement: The normal force on the object is 22 N [up]. $\vec{F}_1$ is 13 N [left].

Practice

1. Explain why it is unsafe to stand when riding a bus or subway without holding onto something. K/U C
2. In a demonstration, a teacher places some plates on top of a smooth tablecloth. The teacher then pulls quickly on the tablecloth. If the tablecloth is a frictionless surface, predict what will happen to the plates. Explain your reasoning. K/U
3. A driver in a car passes over some black ice, which exerts almost no friction on the wheels. Explain why the car cannot slow down when the driver pushes on the brakes. K/U
4. You have some snow stuck on your shovel. Explain how you could apply Newton's first law to get the snow off. K/U
5. The FBD in **Figure 8** is for a car at rest on the ground. T/I
   (a) Determine $\vec{F}_1$ and $\vec{F}_g$. [ans: $\vec{F}_1 = 2650$ N [R]; $\vec{F}_g = 13\ 000$ N [down]]
   (b) How would your answers change if the car was moving at a constant velocity? Assume none of the given forces change.

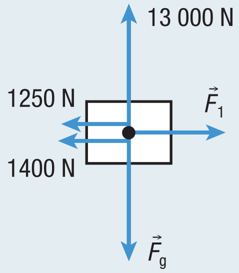


Figure 8

Mini **Investigation**

Testing Newton’s First Law

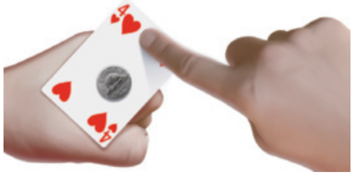
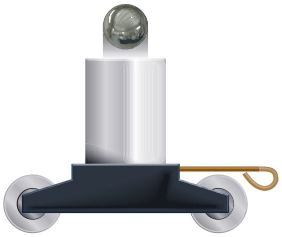
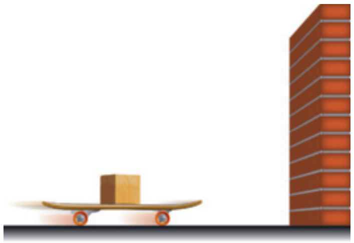
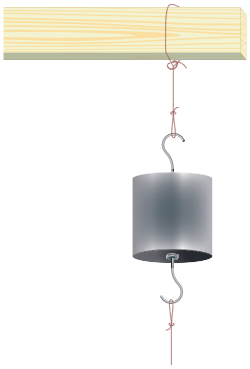
Skills: Observing, Analyzing, Communicating

Your teacher will present several situations and ask you to predict what will happen and explain your reasoning. You will then observe the demonstration and record what happens. Finally, you will explain what happens and why in terms of Newton’s first law.

Equipment and Materials: coin; playing card; ballistics cart and ball; skateboard; thread; two standard masses

1. Create a table in your notebook similar to **Table 1**. The second column in Table 1 shows a sketch of each demonstration. Summarize your results in the appropriate column of your table. T/I C

Table 1

Situation	Sketch of situation	Prediction/ explanation	Observations	Explanation
A. A coin is on top of a playing card on the left fist. Hit the card.				
B. A moving ballistics cart fires a ball by exerting a force straight up.				
C. A moving skateboard with an object on top hits a wall.				
D. A thread supports an object. Another thread is underneath. Pull slowly on the bottom thread.				
E. A thread supports an object. Another thread is underneath. Pull quickly on the bottom thread.				

Applications of Newton's First Law

A wide range of technologies take advantage of Newton's first law including automobiles, planes, rockets, and construction. The key idea is that the net force must be zero for any object to remain at rest or to keep moving with uniform motion.

Consider the physics of a typical seat belt. What will happen if you are not wearing a seat belt and the car suddenly stops? According to Newton's first law, you will continue to move forward at a constant velocity until an object exerts a net force on you. This could be the dashboard or the windshield. If you are wearing a seat belt, the seat belt will exert a net force on you to slow you down.

WEB LINK

To learn more about how seat belts work,

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One design feature of a seat belt uses the sudden decrease in velocity of the car to activate a gear mechanism. In this design, the seat belt strap is attached to a spool, which in turn is attached to a gear (**Figure 9**). Beneath this gear is a pendulum that is free to swing back and forth. When the car comes to a sudden stop, the pendulum swings forward due to inertia. This causes the pendulum to move a metal stop into the teeth of the gear, locking the seat belt in place.

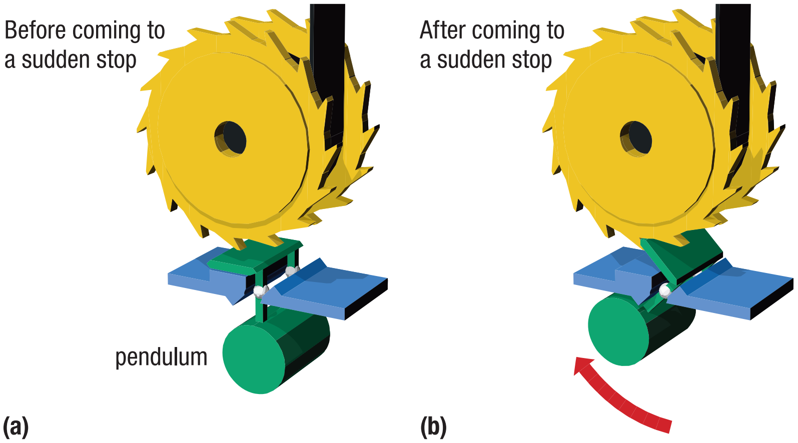

Figure 9 (a) When the vehicle is moving at constant velocity the seat belt pendulum (shown in green) hangs straight down. (b) After a sudden stop, the pendulum swings, causing the metal stop to lock into the seat belt gear.

Space and flight technology also takes advantage of Newton's first law. During high accelerations in a jet or a rocket, a pilot or astronaut might experience pooling of blood in certain parts of the body such as the legs. The inertia of the blood often causes it to move out of the head and into the legs. A G-suit helps to prevent this condition by exerting pressure on the legs and lower torso. In effect, it is squeezing the blood out of the legs back up toward the brain.

UNIT TASK BOOKMARK

You can apply what you learned about Newton's first law to the Unit Task described on page 204.

3.2 Summary

- Inertia is the property of matter that causes it to resist changes in motion. Inertia is directly proportional to the mass of the object.
- Newton's first law can also be called the law of inertia. Newton's first law states that if the net force acting on an object is zero, the object will either remain at rest or continue to move at a constant velocity.
- There are many implications of Newton's first law: objects at rest tend to remain at rest; objects in motion tend to remain in motion; if the velocity of an object is constant, then the net force is zero; if a net force acts on an object, the velocity will change in magnitude, direction, or both.
- Newton's first law of motion can be applied in many situations to help increase our understanding of motion.
- Newton's first law of motion has many technological applications.

3.2 Questions

1. Explain how modern technology can help demonstrate Galileo's thought experiments. K/U
2. Which has the most inertia, a truck, a desk, or a feather? Which has the least inertia? How do you know? K/U
3. Skater 1 has a mass of 45 kg and is at rest. Skater 2 has a mass of 50 kg and is moving slowly at a constant velocity of 3.2 m/s [E]. Skater 3 has a mass of 75 kg and is moving quickly at a constant velocity of 9.6 m/s [E]. Which skater experiences the greater net force? Explain your reasoning. K/U
4. Explain each statement using inertia or Newton's first law. K/U
    (a) You should not sit in the back (bed) of a pickup truck when it is moving.
    (b) It is hard to get a car moving on very slippery ice.
    (c) You should not put objects on the ledge of a car between the rear windshield and the rear seat.
    (d) During liftoff, astronauts are placed horizontally in the capsule rather than vertically.
5. Headrests and seat belts are two important pieces of safety equipment used in automobiles. K/U
    (a) Will both technologies significantly improve safety if the car suddenly slows down but keeps moving in a straight line? Explain your reasoning.
    (b) Will both technologies significantly improve safety if the car suddenly speeds up but keeps moving in a straight line? Explain your reasoning.
6. Many people buy a coffee or other hot beverage on their way to work. For safety, the cup usually has a lid and is placed in a cup holder. Using Newton's first law, explain why both of these precautions are necessary. C A
7. **Figure 10** shows a string tied to a spike at one end and a puck at the other. The puck is moving around in a circle on the ice. Describe what the puck will do if the string is suddenly cut at the red line. Explain your reasoning using a diagram. K/U C

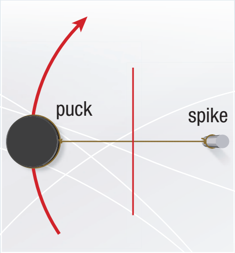

Figure 10

8. Use Newton's first law to explain why the normal force must be equal in magnitude to the force of gravity for an object to remain at rest on a horizontal surface when no other forces are acting on the object. K/U C
9. You are inside a car moving fast along a sharp turn in the road. Use Newton's first law to describe what happens to you as you safely make it around the curve. T/I C
10. Use Newton's first law to explain why you should slow down when going around a curve on an icy highway. K/U C
11. **Figure 11** shows some simple equipment used to test Newton's first law. In the experiment, the ring is suddenly pulled horizontally. T/I C
    (a) Predict what will happen to the piece of chalk. Explain your reasoning.
    (b) Why does it help to put some water in the container?

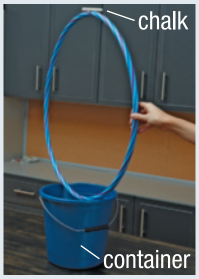

Figure 11

12. While on the bus, you throw an apple straight up into the air. What will happen if the bus
    (a) moves at a constant velocity?
    (b) slows down?
    Explain your reasoning using diagrams. T/I C
13. Determine the indicated forces on each FBD shown in **Figure 12.** T/I
    (a) statue at rest on a shelf
    (b) sled pulled right at a constant velocity

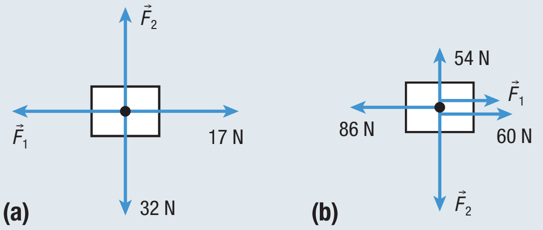

Figure 12

14. Your physics teacher challenges the class to the following puzzle. Place eight quarters into a single stack on a desk. Your task is to take the stack apart one quarter at a time using only a thin ruler. You cannot make any contact with the quarters but the ruler can. Only quarters at the bottom of the pile may be removed. T/I C
    (a) Describe how you would complete the task. Carry out your plan to test whether it works.
    (b) Explain why it works.
15. Studies reveal that many people do not use their headrest properly. Research what most people do wrong and how it can be fixed. Prepare a small pamphlet that can be used to make people aware of the problem and how to fix it. Include any useful statistics that might encourage people to make the necessary changes. T/I C

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3.3 Newton's Second Law of Motion

Newton's first law of motion applies to situations when the net force on an object is zero. When the net force is zero, an object that is at rest will remain at rest and an object that is in motion will continue to move in a straight line at a constant velocity. What do these cases have in common? In both cases, the acceleration is zero.

The Variables Involved in Newton's Second Law

One way to experience Newton's second law of motion is in a moving car. A light car with a powerful engine that can exert a large force will experience a large acceleration (**Figure 1(a)**). A massive truck experiences small accelerations even if the force is large (**Figure 1(b)**). A small economy car experiences smaller accelerations because the force its engine exerts is smaller (**Figure 1(c)**). The acceleration is affected by changing either the mass or the net force. To understand this relationship among acceleration, net force, and mass, we need to consider these variables more carefully.

Figure 1 (a) A race car speeds up quickly because it has a small mass and experiences a large net force. (b) A truck accelerates more slowly. Even though a large net force acts on it, the mass is large. (c) A small economy car also accelerates more slowly. It has a small mass and a small applied force.

We will first examine the relationship between the net force and the acceleration. Imagine pushing a large sled with a few small boxes on top across a nearly frictionless icy surface. If you push as hard as you can, the sled starts from rest and attains a high velocity in little time (**Figure 2(a)**). If you push with less force on the sled, the velocity will increase more gradually (**Figure 2(b)**). These two scenarios imply that acceleration increases as the net force increases. Now we will examine the effect of mass on acceleration. If you remove the boxes, the lighter sled is easier to speed up from rest (**Figure 2(c)**). If you put more boxes on the sled, the heavier sled is harder to speed up at the same rate (**Figure 2(d)**). In other words, acceleration decreases as mass increases.

WEB LINK

To learn more about how forces are applied to sports,

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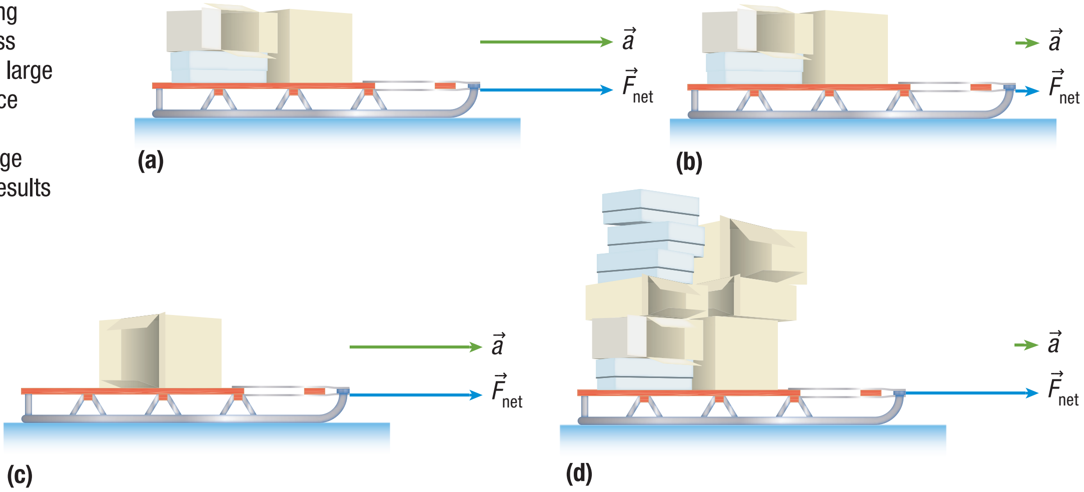
Figure 2 The relationship among acceleration, net force, and mass (a) A large net force results in a large acceleration. (b) A small net force results in a small acceleration. (c) A small mass results in a large acceleration. (d) A large mass results in a small acceleration.



Newton's **second law of motion** is summarized as follows:

second law of motion an object will accelerate in the direction of the net force; the magnitude of the acceleration is directly proportional to the magnitude of the net force and inversely proportional to the object's mass

Second Law of Motion

If the net external force on an object is not zero, the object will accelerate in the direction of this net force. The magnitude of the acceleration is directly proportional to the magnitude of the net force and inversely proportional to the mass of the object.

Representing Newton's Second Law Mathematically

From Newton's second law, we can derive an equation that connects acceleration, net force, and mass.

$$\vec{a} \propto \vec{F}_{\text{net}} \text{ when } m \text{ is constant} \quad \text{and} \quad \vec{a} \propto \frac{1}{m} \text{ when } \vec{F}_{\text{net}} \text{ is constant}$$

Combining the two proportionalities, we get

$$\vec{a} \propto \frac{\vec{F}_{\text{net}}}{m}$$

We can create an equation relating all three variables if we insert a proportionality constant k:

$$\vec{a} = k\frac{\vec{F}_{\text{net}}}{m}$$

If we define the newton as the net force required to accelerate 1 kg at 1 m/s^2 or 1 N = 1 kg·m/s^2, then $k = 1$. We can write the equation as

$$\vec{a} = \frac{\vec{F}_{\text{net}}}{m}$$

Solving for the net force, we have

$$\vec{F}_{\text{net}} = m\vec{a}$$

Consider a situation where the mass is kept constant but the net force gradually increases. From the equation $\vec{F}_{\text{net}} = m\vec{a}$, if mass is kept constant and the net force on the object increases, the acceleration also increases. If you graph net force versus acceleration, the relationship is linear (**Figure 3**).

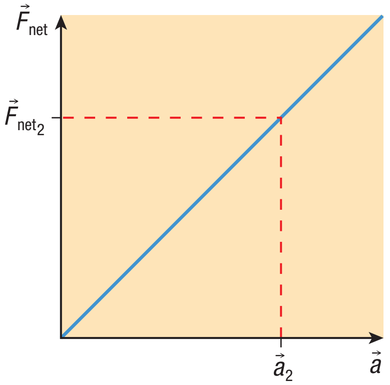


Figure 3 The graph of net force versus acceleration is linear, and the slope represents the mass. The line must pass through the origin, since when the acceleration is zero the net force must also be zero.

Consider the slope of the line:

$$\begin{aligned}\text{slope} &= \frac{\text{rise}}{\text{run}} \\ &= \frac{\Delta\vec{F}_{\text{net}}}{\Delta\vec{a}}\end{aligned}$$

The line must pass through the origin. From Newton's first law, when the acceleration is zero, the net force must also be zero. If we use the origin as the initial point on the graph, the above slope equation simplifies to

$$\begin{aligned}\text{slope} &= \frac{\vec{F}_{\text{net}_2} - \vec{F}_{\text{net}_1}}{\vec{a}_2 - \vec{a}_1} \\ &= \frac{\vec{F}_{\text{net}_2} - 0}{\vec{a}_2 - 0} \\ &= \frac{\vec{F}_{\text{net}_2}}{\vec{a}_2}\end{aligned}$$

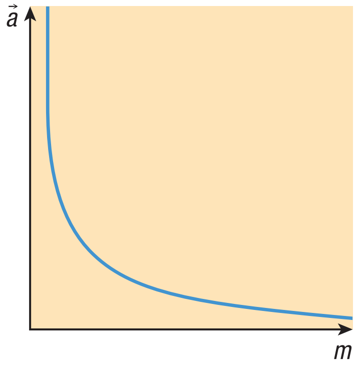


Figure 4 The graph of acceleration versus mass is a reciprocal function.

Physically, what does this slope represent? Using Newton's second law, we have

$$\vec{F}_{\text{net}} = m\vec{a}$$

$$m = \frac{\vec{F}_{\text{net}}}{\vec{a}}$$

The expressions for slope and mass can be equated, so we can conclude that the slope of the graph of net force versus acceleration is the mass of the object.

Now consider a situation where the net force is kept constant but the mass gradually increases. From the equation $\vec{a} = \frac{\vec{F}_{\text{net}}}{m}$, if the net force is kept constant and the mass of an object increases, the acceleration decreases. If you graph acceleration versus mass, the graph shows a reciprocal relationship (**Figure 4**).

Tutorial 1 Using Newton's Second Law

Newton's second law can be used to solve a variety of problems involving many different situations. In the following Sample Problems, we will demonstrate how to apply Newton's second law.

Sample Problem 1: Determining Acceleration

A net force of 36 N [forward] is applied to a volleyball of mass 0.24 kg. Determine the acceleration of the volleyball.

Given: $\vec{F}_{\text{net}} = 36$ N [forward]; $m = 0.24$ kg

Required: $\vec{a}$

Analysis: $\vec{F}_{\text{net}} = m\vec{a}$. Choose forward as positive.

Solution: $\vec{F}_{\text{net}} = m\vec{a}$

$$\vec{a} = \frac{\vec{F}_{\text{net}}}{m}$$

$$a = \frac{+36\text{ N}}{0.24\text{ kg}}$$

$$a = +150\text{ m/s}^2$$

$$\vec{a} = 150\text{ m/s}^2\ [\text{forward}]$$

Statement: The acceleration of the volleyball is 150 m/s^2 [forward].

Sample Problem 2: Calculating Net Force

A 64 kg runner starts walking at 3.0 m/s [E] and begins to speed up for 6.0 s, reaching a final velocity of 12.0 m/s [E]. Calculate the net force acting on the runner.

Given: $m = 64$ kg; $\vec{v}_1 = 3.0$ m/s [E]; $\vec{v}_2 = 12.0$ m/s [E]; $\Delta t = 6.0$ s

Required: $\vec{F}_{\text{net}}$

Analysis: $\vec{F}_{\text{net}} = m\vec{a}$, but first we have to calculate the acceleration using the kinematics equation $\vec{a} = \frac{\vec{v}_2 - \vec{v}_1}{\Delta t}$.

Choose east as positive.

Solution: $\vec{a} = \frac{\vec{v}_2 - \vec{v}_1}{\Delta t}$

$$a = \frac{+12.0\text{ m/s} - (+3.0\text{ m/s})}{6.0\text{ s}}$$

$$a = +1.5\text{ m/s}^2$$

$$\vec{a} = 1.5\text{ m/s}^2\ [\text{E}]$$

Now we can calculate the net force.

$$\vec{F}_{\text{net}} = m\vec{a}$$

$$F_{\text{net}} = (64\text{ kg})(+1.5\text{ m/s}^2)$$

$$F_{\text{net}} = +96\text{ N}$$

$$\vec{F}_{\text{net}} = 96\text{ N}\ [\text{E}]$$

Statement: The net force on the runner is 96 N [E].

Sample Problem 3: Calculating Net Force and Acceleration Using an FBD

A 9100 kg jet moving slowly on the ground fires its engines, resulting in a force of 22 000 N [E] on the jet. The force of friction on the jet is 3800 N [W].

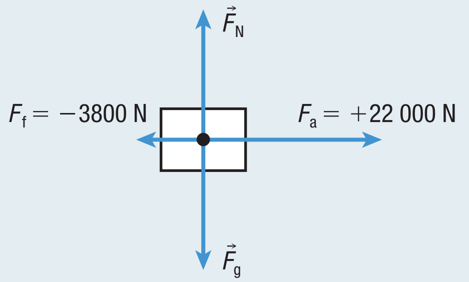
(a) Draw the FBD for the jet.

(b) Calculate the net force acting on the jet.

(c) Calculate the acceleration of the jet.

Solution

(a) Choose up and east as positive. So down and west are negative.



(b) The normal force and gravity will cancel when the jet is on horizontal ground. The net force is east since the applied force is greater than the force of friction. To find the net force, we add all the horizontal forces.

$$\begin{aligned}\vec{F}_{net} &= \vec{F}_a + \vec{F}_f \\ F_{net} &= +22\,000\text{ N} + (-3800)\text{ N} \\ F_{net} &= +18\,200\text{ N} \\ \vec{F}_{net} &= 18\,200\text{ N [E]}\end{aligned}$$

The net force on the jet is 18 200 N [E].

(c) **Given:** $\vec{F}_{net} = 18\,200$ N [E]; $m = 9100$ kg

Required: $\vec{a}$

Analysis: $\vec{F}_{net} = m\vec{a}$

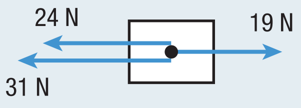
Solution: $\vec{F}_{net} = m\vec{a}$

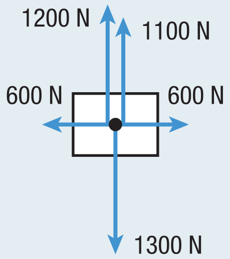
$$\begin{aligned}\vec{a} &= \frac{\vec{F}_{net}}{m} \\ a &= \frac{+18\,200\text{ N}}{9100\text{ kg}} \\ a &= +2.0\text{ m/s}^2 \\ \vec{a} &= 2.0\text{ m/s}^2\text{ [E]}\end{aligned}$$

Statement: The acceleration of the jet is 2.0 m/s^2 [E].

Practice

1. A net force of 126 N [S] is applied to a 70 kg sprinter. Determine the acceleration of the sprinter. T/I [ans: 1.8 m/s^2 [S]]
2. A car accelerates at 1.20 m/s^2 [forward]. The net force on the car is 1560 N [forward]. What is the mass of the car? T/I [ans: 1300 kg]
3. A cyclist starts to pedal vigorously, increasing her velocity from 6.0 m/s [E] to 14.0 m/s [E] in 6.0 s. The total mass of the cyclist and the bicycle is 58 kg. Find the net force acting on the cyclist and bicycle. T/I [ans: 77 N [E]]
4. During a road test, a driver brakes a 1420 kg car moving at 64.8 km/h [W]. The car slows down and comes to a stop after moving 729 m [W]. T/I
   (a) Calculate the net force acting on the car. [ans: 316 N [E]]
   (b) What is the force of friction acting on the car while it is slowing down? Explain your reasoning. [ans: 316 N [E]]
5. For each FBD shown below, determine the net force applied to the object and its acceleration. T/I
   (a) $m = 8.0$ kg [ans: 36 N [left], 4.5 m/s^2 [left]] (b) $m = 125$ kg [ans: 1000 N [up], 8 m/s^2 [up]]





6. In a two-person bobsled competition, athlete 1 pushes forward on the sled with 310 N and athlete 2 pushes forward with 354 N. A force of friction of 40 N [backwards] is acting on the bobsled. The mass of the bobsled is 390 kg. Calculate the acceleration of the bobsled. T/I [ans: 1.6 m/s^2 [forward]]

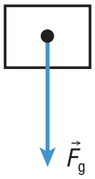


Figure 5 This FBD shows an object in free fall, with no air resistance acting on it. The net force on the object is the force of gravity. The acceleration of the object is equal to the acceleration due to gravity.

Newton's Second Law and Gravity

In Section 3.1, you learned that you can calculate the force of gravity by multiplying the mass by the acceleration due to gravity. We can now justify the equation $\vec{F}_g = m\vec{g}$ using Newton's second law.

Consider an object in free fall with no air resistance acting on it (**Figure 5**). Free fall is motion of an object toward Earth with no other forces acting on it. The only force acting on the object is the force of gravity. In this situation, the force of gravity is equal to the net force. We also know that the object accelerates down at $\vec{a} = 9.8 \text{ m/s}^2$ [down]. Combining these two facts, we have

$$\vec{F}_g = \vec{F}_{net}$$
$$= m\vec{a}$$

Then, because $\vec{a} = \vec{g}$,

$$\vec{F}_g = m\vec{g}$$

You will use the equation for the force of gravity to help you complete **Investigation 3.3.1**. To prepare for the investigation, read the following Tutorial and complete the Practice questions.

Tutorial 2 Acceleration of Falling Objects

Recall that strings can only pull on objects when they exert tension. A pulley is a small wheel that changes the direction of the tension in a rope or string without changing its magnitude. We will assume throughout the text that all pulleys are frictionless and light.

Sample Problem 1

In an investigation, students place a 0.80 kg cart on a table. They tie one end of a light string to the front of the cart, run the string over a pulley, and then tie the other end to a 0.20 kg hanging object (**Figure 6**). Assume that no friction acts on either object.

(a) Determine the magnitude of the acceleration of the cart and the hanging object.

(b) Calculate the magnitude of the tension.

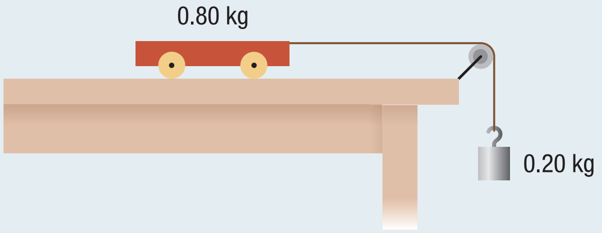
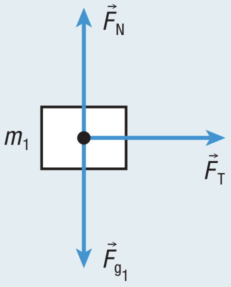


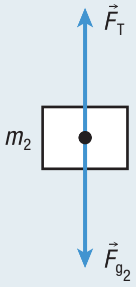
Figure 6

(a) **Step 1.** Draw the FBD for each object.

FBD of cart



FBD of hanging object



Step 2. Identify which directions are positive. Determine the net force acting on each object.

The cart is on the table, so the normal force and gravity cancel each other. The cart will accelerate to the right, so choose right as positive. The equation for the net force acting on the cart is

$F_{net} = F_T$

Because $F_{net} = m_1a$,

$m_1a = F_T$ (Equation 1)

The hanging object will accelerate down, so choose down as positive. The equation for the net force acting on the hanging object is

$F_{net} = F_{g_2} - F_T$

Because $F_{net} = m_2a$ and $F_{g_2} = m_2g$,

$m_2a = m_2g - F_T$ (Equation 2)

Step 3. Add the equations to solve for the acceleration.

The tension acting on the cart and on the hanging object is the same. Adding equations 1 and 2 will cancel the tension.

$$\begin{aligned} m_1a + m_2a &= F_T + m_2g - F_T \\ m_1a + m_2a &= m_2g \\ (m_1 + m_2)a &= m_2g \\ (0.80 \text{ kg} + 0.20 \text{ kg})a &= (0.20 \text{ kg})(9.8 \text{ m/s}^2) \\ a &= 1.96 \text{ m/s}^2 \\ a &= 2.0 \text{ m/s}^2 \end{aligned}$$

The magnitude of the acceleration of the cart is 2.0 m/s^2.

(b) To calculate the tension, substitute the acceleration into equation 1.

$$m_1 a = F_T$$
$$F_T = (0.80\ \text{kg})(1.96\ \text{m/s}^2)$$
$$F_T = 0.16\ \text{N}$$

The magnitude of the tension in the string is 0.16 N.

Practice

1. Calculate the acceleration of the cart in **Figure 7**, given the following assumptions. T/I
   (a) No friction is acting on the cart. [ans: 3.3 m/s^2 [right]]
   (b) A force of friction of 0.50 N acts on the cart opposite to the motion. [ans: 3.0 m/s^2 [right]]

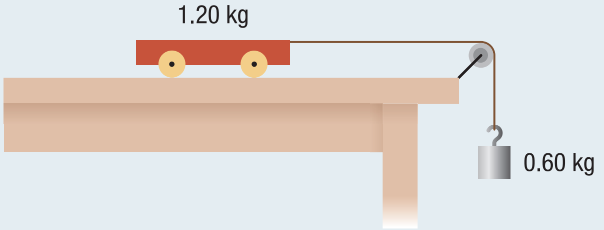


Figure 7

2. In an experiment, objects are placed on top of a cart as shown in **Figure 8**. T/I

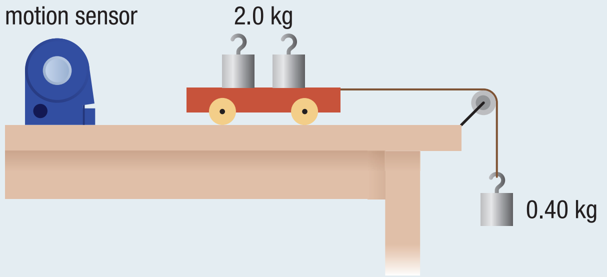


Figure 8

   (a) Calculate the acceleration of the cart. Assume that no friction acts on the cart. [ans: 1.6 m/s^2 [right]]
   (b) What will happen to the acceleration of the cart if the mass of the objects on top of the cart increases? Explain your reasoning.
   (c) What will happen to the acceleration of the cart if an object is taken from the top of the cart and tied to the hanging object? Explain your reasoning.

3.3 Summary

- According to Newton's second law, when a non-zero net force acts on an object, the object will accelerate in the direction of the net force. The acceleration is directly proportional to the net force and inversely proportional to the mass. The equation representing Newton's second law is $\vec{F}_{\text{net}} = m\vec{a}$.
- If the net force on an object increases and the mass is constant, then the acceleration increases. If the net force on an object is constant and the mass increases, then the acceleration decreases.
- When solving problems where more than one force acts on a single object, make sure you draw an FBD. You can add all the forces to calculate the net force. You can also use the equation $\vec{F}_{\text{net}} = m\vec{a}$.
- For a falling object, Newton's second law can be used to justify that $\vec{F}_g = m\vec{g}$.

Investigation **3.3.1**

Investigating Newton's Second Law (p. 150)
Now that you have learned about Newton's second law, you can perform Investigation 3.3.1. You will explore how changing the net force acting on a system affects the acceleration of the system. You will also explore how changing the mass of the system affects the acceleration of the system.

3.3 Questions

1. Calculate the net force in each situation. T/I
   - (a) A 72 kg rugby player accelerates at 1.6 m/s^2 [forward].
   - (b) A 2.3 kg model rocket accelerates at 12 m/s^2 [up].
2. Calculate the acceleration in each situation. T/I
   - (a) A cannon exerts a force of 2.4×10^4 N [E] on a 5.0 kg shell.
   - (b) A hockey stick hits a 160 g puck forward with a force of 24 N.
3. Determine the mass of the object in each situation. T/I
   - (a) A driver brakes and the car accelerates at 1.2 m/s^2 [backwards]. The net force on the car is 1400 N [backwards].
   - (b) A woman throws a shot put with a net force of 33 N [forward] with an acceleration of 6.0 m/s^2 [forward].
4. A 54 kg skier starts from rest at the top of a snow-covered hill, reaching a velocity of 12 m/s in 5.0 s. Calculate the net force acting on the skier. T/I
5. A dynamics cart is pulled from rest by a net force of 1.2 N [forward]. The cart moves 6.6 m, reaching a velocity of 3.2 m/s [forward]. Determine the mass of the cart. T/I
6. During a parachute jump, a 58 kg person opens the parachute and the total drag force acting on the person is 720 N [up]. T/I
   - (a) Calculate the net force acting on the person.
   - (b) Determine the acceleration of the person.
7. A net force of magnitude 36 N gives an object of mass m_1 an acceleration of 6.0 m/s^2. The same net force gives m_1 and another object of mass m_2 fastened together an acceleration of 2.0 m/s^2. What acceleration will m_2 experience if the same net force acts on it alone? T/I
8. A 1300 kg car accelerates at 1.6 m/s^2 [E]. A frictional force of 3800 N [W] is acting on the car. T/I C
   - (a) Draw the FBD of the car.
   - (b) Determine the applied force acting on the car.
9. A long, heavy, metal chain is held at rest on a table with part of the chain hanging over the edge (**Figure 9**). The chain is released and it starts to accelerate. K/U

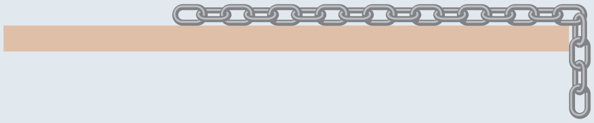


Figure 9

   - (a) In which direction will the chain accelerate? What causes the acceleration? Explain your reasoning.
   - (b) What will happen to the acceleration of the chain as more chain moves over the edge of the table? Explain your reasoning.
10. Three students push horizontally on a large 80 kg crate sitting on the floor. Two of them push to the left on the crate, each with a force of 170 N. The third pushes to the right on the crate with a force of 150 N. Assume that no friction acts on the crate. T/I
    - (a) What is the acceleration of the crate?
    - (b) What will happen to the net force and acceleration if a fourth student jumps on top of the crate? Explain your reasoning.
11. A string can hold up 12 kg without breaking. You tie the string to a 30 kg object sitting on ice and use it to pull the object horizontally for 22 m. Calculate the minimum possible time to complete the task. T/I
12. Examine the data in **Table 1**. T/I C
    - (a) Copy and complete the table.
    - (b) Graph $\vec{F}_a$ versus $\vec{a}$ and draw the line of best fit. What does the *y*-intercept represent? Explain.
    - (c) Graph $\vec{F}_{net}$ versus $\vec{a}$ and draw the line of best fit. Calculate the slope of the line. What does the slope represent? Explain.

Table 1

Mass (kg)	Friction (N) [W]	Applied force (N) [E]	Net force (N) [E]	Acceleration (m/s^2) [E]
4.0	9.0	9.0		
4.0	9.0	13.0		
4.0	9.0		8.4	
4.0	9.0			3.5

Newton’s Third Law of Motion

3.4

Examine the photograph in **Figure 1** of an Atlas V rocket during liftoff. What forces are acting on the rocket? An obvious one is gravity pulling the rocket down. The rocket is accelerating upward in the picture. This means that the net force must be up according to Newton’s second law. What is this upward force? You might suggest that the ground is pushing up on the rocket with the normal force. This cannot be the answer because the normal force is a contact force and the rocket is no longer in contact with the ground. In this section, you will learn about this upward force as you learn about Newton’s third law of motion.

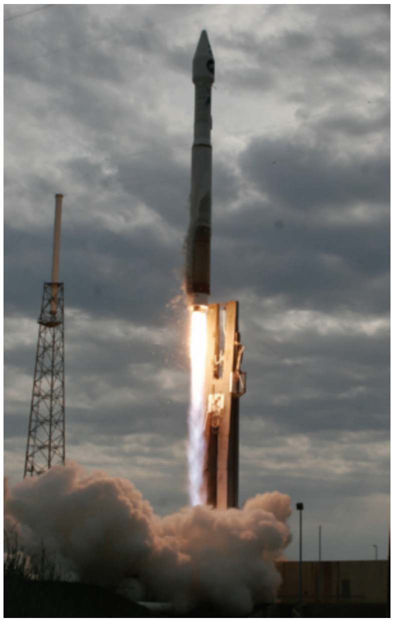


Figure 1 An Atlas V rocket was launched in June 2009. As the rocket lifted up off the launch pad, what force caused it to accelerate upward?

Action and Reaction Forces

If you reach out and push this book away from you, you can actually feel the book pushing back on you. This is an example of a set of action and reaction forces. The action force is you pushing on the book, and the reaction force is the book pushing back on you. An easy way to experience action and reaction forces is by pushing on the boards when you are skating in an ice rink. When you push on the boards (the action force), the boards push back on you (reaction force). It is the reaction force that causes you to accelerate away from the boards.

These action and reaction forces are all around us and go unnoticed most of the time. When you push a door open, the door pushes back on you. When you walk forward across the floor, you push backwards on the ground and the ground pushes forward on you. In fact, whenever one object exerts a force on another, the second object exerts another force back.

Another simple way to demonstrate action and reaction forces is to have a person standing at rest on a skateboard suddenly step forward (**Figure 2**). When this happens, the person and the skateboard will accelerate in opposite directions. According to Newton’s second law, both the person and the skateboard have net forces acting on them because they are accelerating. What causes these forces?

The net force on the skateboard is caused by the person’s feet pushing backwards on the skateboard. The person’s feet exert the action force on the skateboard. The net force on the person is caused by the skateboard pushing forward on the person. The skateboard exerts the reaction force on the person.

Keep in mind that these action and reaction forces are simultaneous. It is incorrect to imply that the action force happens first and then the reaction force happens. These are contact forces, and both the action and reaction forces start whenever contact is made.

Newton’s **third law of motion** deals with these action and reaction forces. For this reason, it is sometimes called the action–reaction law.

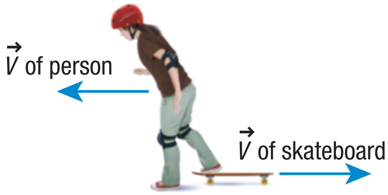


Figure 2 As a person jumps off a skateboard in one direction, the skateboard will accelerate in the other direction.

Third Law of Motion

For every action force, there is a simultaneous reaction force that is equal in magnitude, but opposite in direction.

third law of motion each action force has a reaction force that is equal in magnitude and opposite in direction

We can now explain how a rocket can accelerate up off the launch pad. During liftoff, the rocket engines burn rocket fuel, creating tremendous pressure, which causes the expanding hot gases to accelerate from the bottom of the rocket (action force). At the same time, the expanding hot gases push up on the rocket (reaction force), causing the rocket to accelerate up. According to Newton’s third law, the action force caused by the expanding hot gases is equal in magnitude to the reaction force of the expanding hot gases on the rocket. If the reaction force up on the rocket from the expanding hot gases is greater than the force of gravity pulling the rocket down, then the rocket will accelerate up. In the following Tutorial, you will apply Newton’s third law to problems involving motion.

Tutorial 1 Explaining Motion Using Newton's Third Law

In the following Sample Problem, we will clarify Newton's third law and demonstrate how it can be used to explain motion when objects exert forces on each other.

Sample Problem 1

Explain each event in terms of Newton's third law.

(a) A swimmer moves through the water.
(b) A small balloon releases air and flies around the classroom.
(c) You start walking across the floor.

Solution

(a) The swimmer's arms and legs exert an action force backwards on the water, causing the water to accelerate backwards. According to Newton's third law, the water exerts an equal but opposite force forward on the swimmer, propelling the swimmer forward through the water.

(b) As the rubber in the balloon contracts, it forces air out the back of the balloon (action force). According to Newton's third law, the reaction force is caused by the air pushing back on the balloon, which accelerates the balloon forward.

(c) The bottom of your shoe exerts a horizontal backward action force on the floor. According to Newton's third law, the reaction force is caused by friction when the floor pushes forward on your feet. Friction causes you to accelerate forward.

Practice

1. Explain each event in terms of Newton's third law. K/U
   (a) A rocket can accelerate in outer space.
   (b) A motorboat accelerates east in the water.
   (c) Football player 1 tackles football player 2.

Mini Investigation

Demonstrating the Third Law

Skills: Predicting, Performing, Observing, Analyzing, Communicating SKILLS HANDBOOK A2.1

In this investigation, you will perform and observe several actions that involve Newton's third law. Your task is to predict what will happen at each station, observe carefully what actually happens, and explain why it happens.

Equipment and Materials: office chair with wheels; bathroom scale; desk; ballistics cart; fan cart with removable sail

1. Create a table similar to **Table 1** to record your observations. Add six rows to the table.

Table 1

Activity	Prediction	Observation	Action and reaction forces

2. Read through the descriptions of activities (a) through (g). For each activity, predict what you think will happen and record your predictions in your table.
3. Perform activities (a) to (g) (or observe a classmate performing these activities). Record your observations.
   (a) Sit on an office chair and push gently against a wall with both hands.
   (b) Sit on the chair, not touching the wall. Use your hands to pull horizontally on your own shoulders, away from the wall.
   (c) Stand on a bathroom scale placed beside a desk. Put your hands on the desk and push down.
   (d) Stand on a bathroom scale. Push down on your own head with your hands.
   (e) Use a spring-loaded ballistics cart to fire a ball horizontally.
   (f) Obtain a fan cart (**Figure 3(a)**) with no sail. Direct the fan away from the cart. Turn the fan cart on.
   (g) Obtain a fan cart (**Figure 3(b)**) with a sail. Direct the fan toward the sail. Turn the fan cart on.

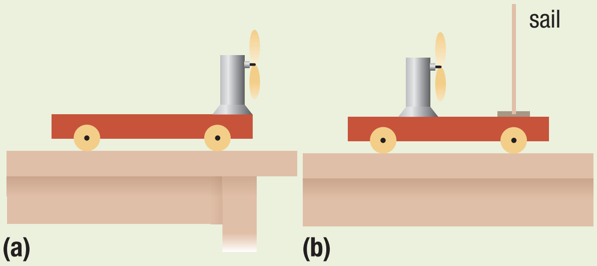


Figure 3

A. Use Newton's third law to describe the action and reaction forces you observed in each activity. T/I

You may have noticed that objects will not always accelerate or the reading on a scale will not always change when a force is applied to an object. What is different about these situations? The difference is that in each of these situations there is no external net force acting on the object.

Does this mean that action and reaction forces cancel and we can never accelerate? Definitely not. Action and reaction forces always act on different objects, or different parts of a single object. When two objects are involved, the two forces are not added together and each object can accelerate.

For example, if a ballistics cart pushes backwards on a ball (action force), the ball accelerates backwards because the applied force causes a net force on the ball. According to Newton's third law, the ball will also cause a reaction force on the cart in the opposite direction. This reaction force causes a net force on the cart, making it accelerate the other way. The action and reaction forces do not cancel because they do not act on the same object. When you draw the FBD for each object, the action and reaction forces will appear in separate FBDs (**Figure 4**).

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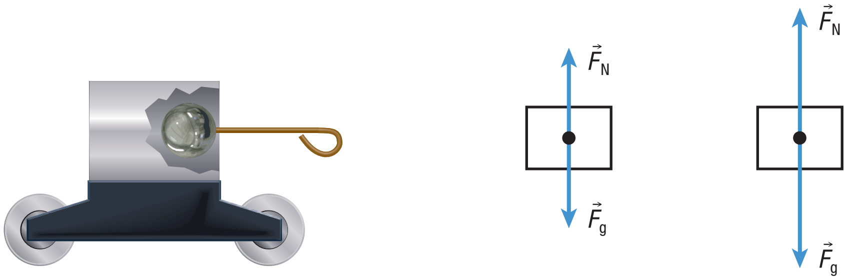
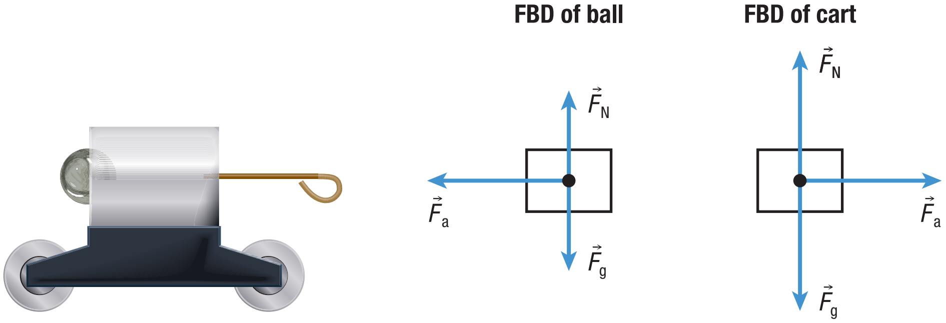


(a) before



(b) after

Figure 4 (a) Diagram and FBDs of a ball inside a ballistics cart before firing (b) Diagram and FBDs after firing the ball. The action and reaction forces do not cancel because they act on different objects.

Tutorial 2 Using Newton's Third Law in Calculations

In the following Sample Problem, we will clarify Newton's third law and demonstrate how it can be used to explain motion when objects exert forces on each other.

Sample Problem 1: One Skater Pushing on Another

Two skaters are standing on ice facing each other (**Figure 5**). Skater 1 pushes on skater 2 with a force of 70 N [E]. Assume that no friction acts on either skater. The mass of skater 1 is 50 kg and the mass of skater 2 is 70 kg.

(a) State the action and reaction forces.
(b) Draw the FBD of each skater.
(c) Describe what will happen to each skater.
(d) Calculate the acceleration of each skater.

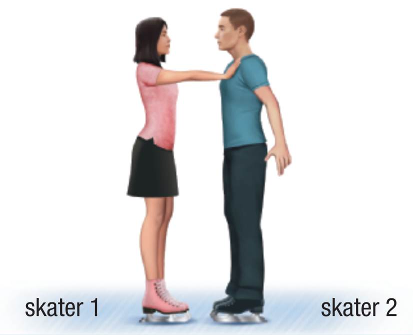
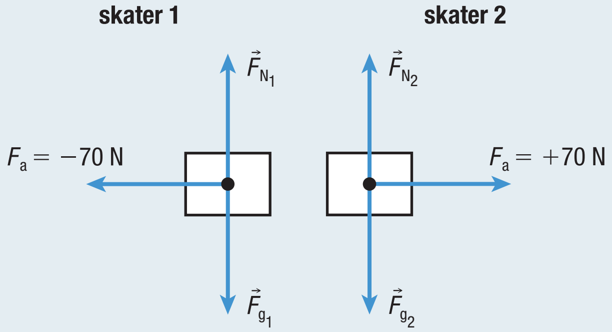


Figure 5

Solution

(a) The action force is skater 1 pushing with 70 N [E] on skater 2. The reaction force is skater 2 pushing with 70 N [W] on skater 1.

(b) Choose east as positive. So west is negative.



(c) Skater 1 will accelerate west and skater 2 will accelerate east.

(d) For each skater, the normal force and the force of gravity cancel. This means that the applied force is equal to the net force. For skater 1,

$$\begin{aligned} \vec{F}_{\text{net}} &= \vec{F}_{a} \\ m_1 a_1 &= -70 \text{ N} \\ (50 \text{ kg})a_1 &= -70 \text{ N} \\ a_1 &= -1.4 \text{ m/s}^2 \end{aligned}$$

The acceleration of skater 1 is 1.4 m/s^2 [W].

Similarly, for skater 2,

$$\begin{aligned} \vec{F}_{\text{net}} &= \vec{F}_{a} \\ m_2 a_2 &= +70 \text{ N} \\ (70 \text{ kg})a_2 &= 70 \text{ N} \\ a_2 &= +1.0 \text{ m/s}^2 \end{aligned}$$

The acceleration of skater 2 is 1.0 m/s^2 [E].

Notice that the two skaters accelerate in opposite directions and with different accelerations. The accelerations do not have the same magnitude because the skaters' masses are different.

Practice

1. Given the action force, describe the reaction force for each situation. K/U C
   (a) You push forward on a book with 5.2 N.
   (b) A boat exerts a force of 450 N [W] on the water.
   (c) A hockey player hits the boards with a force of 180 N [toward the boards].
2. Nobel and Maaham are wearing inline skates. Nobel has a mass of 62 kg and pushes on Maaham, whose mass is 54 kg. Maaham accelerates at 1.2 m/s^2 [left]. Assume that no friction acts on either person. T/I
   (a) Determine the force that Nobel exerts on Maaham. [ans: 65 N [left]]
   (b) Determine Nobel's acceleration. [ans: 1.0 m/s^2 [right]]
3. A horse is tethered to a cart to pull it forward. A student claims, "According to Newton's third law, when the horse pulls forward on the cart, the cart will also pull backwards on the horse. The two objects are attached together, so they cannot accelerate." Discuss the validity of this statement. K/U C
4. A student stands on a skateboard and pushes on a wall with a force of 87 N [S]. The total mass of the student and the skateboard is 58 kg. K/U T/I
   (a) Calculate the acceleration of the student. [ans: 1.5 m/s^2 [N]]
   (b) Explain why the wall does not move.

UNIT TASK **BOOKMARK**

You can apply what you have learned about Newton's third law to the Unit Task on page 204.

3.4 Summary

- Newton's third law always involves situations where two objects exert forces on each other.
- Newton's third law states that for every action force there is a simultaneous reaction force equal in magnitude but opposite in direction.
- When applying Newton's third law, the action and reaction forces will appear on separate FBDs. Since they are on separate FBDs, they are not added together.

3.4 Questions

1. Given each action force, state the reaction force. K/U
   (a) A tire pushes on the road with a force of 240 N [backwards].
   (b) You pull on a desk with a force of 25 N [N].
2. Explain each event below in terms of Newton's third law. K/U
   (a) A squid moves through the water by taking in water and expelling it.
   (b) Walking on a wagon is dangerous.
   (c) A helicopter can hover above the ground.
3. During a space walk, an astronaut notices that her tether is not attached and she is drifting away from the space station. Explain each statement below using Newton's third law. K/U C
   (a) She can pull herself back to the space station if she can reach the space station and pull on it.
   (b) She cannot push herself back to the station by pulling forward on her space suit.
   (c) She can get back to the space station even if she cannot reach it if she is holding a tool.
4. **Figure 6** shows a photograph of an early naval cannon tied to a ship. Explain why the ropes are necessary. A

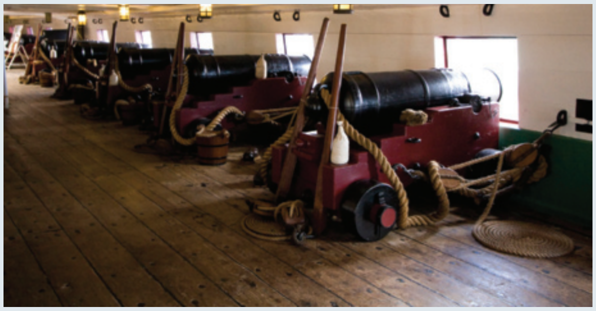


Figure 6

5. **Figure 7** shows a fan cart. K/U
   (a) Explain why the fan cart cannot accelerate.
   (b) Explain why the fan cart can accelerate if the rigid sail is removed.

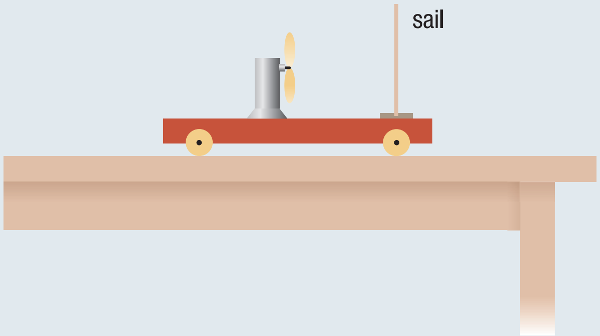


Figure 7

6. A toy car (200 g) moves by shooting a plastic ball (50 g) horizontally out the back. The average acceleration of the car is 1.2 m/s^2 [E] and there is negligible friction acting on each part of the toy. T/I C
   (a) Draw an FBD for each object.
   (b) Identify the action and reaction forces on each part of the toy.
7. Two figure skaters are moving east together during a performance. Skater 1 (78 kg) is behind skater 2 (56 kg) when skater 2 pushes on skater 1 with a force of 64 N [W]. Assume that no friction acts on either skater. T/I
   (a) Determine the acceleration of each skater.
   (b) What will happen to the motion of each skater? Explain your reasoning.
8. A milk carton filled with water is hanging from a string (**Figure 8**). What will happen if you punch two holes in opposite sides of the carton at the opposite corners? Explain your reasoning. T/I

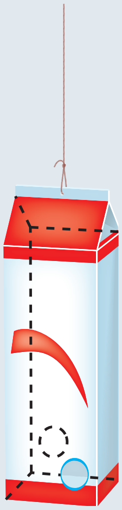


Figure 8

9. A male astronaut (82 kg) and a female astronaut (64 kg) are floating side by side in space. T/I
   (a) Determine the acceleration of each astronaut if the woman pushes on the man with a force of 16 N [left].
   (b) How will your answers change if the man pushes with 16 N [right] on the woman instead?
   (c) How will your answers change if they both reach out and push on each other's shoulders with a force of 16 N?

3.5 Using Newton’s Laws

Newton’s three laws of motion apply to many different situations everywhere around you. They can be used to determine if a train locomotive can make it through a mountain pass while pulling many cars behind it. The laws can also be used to design devices such as prosthetic limbs and bridges (**Figure 1**). To understand how to design these types of devices, you need to know how to apply all three of Newton’s laws, and you need to know how they are related to each other. For example, forces act on a prosthetic leg to accelerate it so a person can walk. The tension in suspension bridge cables helps to hold up the roadway against the force of gravity.

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Figure 1 Newton’s three laws of motion are used to design devices such as (a) prosthetic limbs and (b) bridges.

In this section, you will practise using all three laws together to solve more complex and interesting problems involving forces and motion. In addition, you will learn more about forces, such as tension, and how to use kinematics to understand motion problems more clearly.

Tension and Newton’s Laws

Recall that tension is a pulling force exerted by a device such as a rope or a string. In this course, you may assume that the ropes or strings are light and do not stretch. This means that you do not have to include the mass of the string when calculating the acceleration of two objects tied together. It also means that the tension is uniform throughout the rope or string and pulls with the same force at both ends. Keep in mind that ropes and strings can only pull. This means that tension always acts on the object directed toward the rope or the string.

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For example, two masses are tied together with a string, and a horizontal applied force pulls m_1 to the right (**Figure 2**). If the string exerts a tension of 20 N [left] on m_1, then it also exerts a tension of 20 N [right] on m_2. This is a direct consequence of Newton’s third law and the fact that the string does not stretch and has negligible mass.

How can we measure tension directly? One way is with a force sensor or a spring scale. If you tie opposite ends of a string to two separate force sensors and then pull on the string in opposite directions, you can easily see that the readings on both sensors are the same (**Figure 3**). Again, this is a direct consequence of Newton’s third law and our assumptions about strings. A single force sensor or spring scale can be used to measure the tension in strings if it is tied between two strings (**Figure 4**).

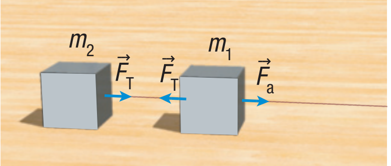


Figure 2 Two objects tied together with a string. The tension force at both ends of the string is the same.

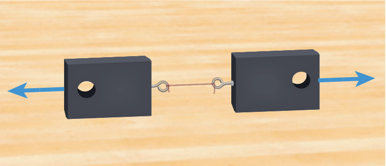


Figure 3 Two force sensors tied together with a string. The readings on the sensors will be equal according to Newton’s third law.

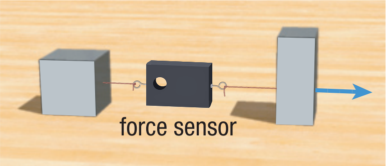


Figure 4 Force sensors can be used to measure tension in strings.

Keep in mind that when two objects are tied together with a single string, if you drag one object forward, the other will also move forward once the string becomes taut. This means that the two objects will move with the same acceleration when they are pulled in a straight line. In this case, tension is an internal force and can be ignored if you are calculating the acceleration of both objects.

Since the tension is the same throughout the string and the tension pulls in opposite directions at the ends, we often just calculate the magnitude of the tension and refer to the FBD for the direction. The following Tutorial will help you to practise solving problems that involve tension and Newton's laws.

Tutorial 1 Solving Tension Problems

To solve the following Sample Problems, we will use Newton's laws and our knowledge of tension. Each problem will help clarify some of the concepts about tension.

Sample Problem 1: Objects Hanging from Strings

Each object in **Figure 5** has a force of gravity of 120 N [down] acting on it. Determine the tension in each string.

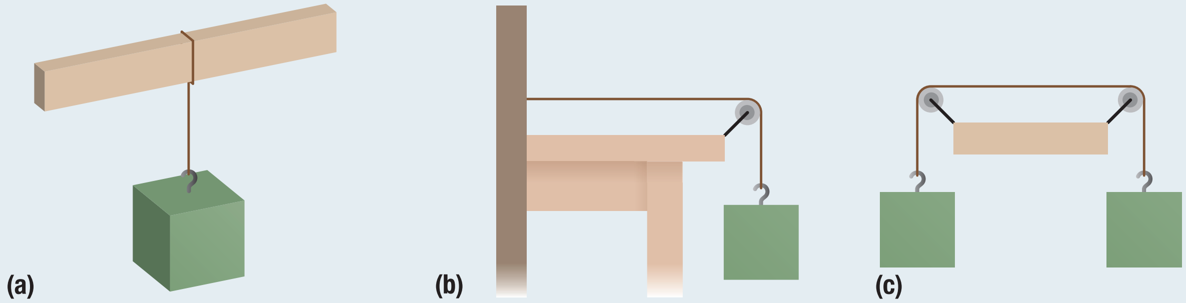
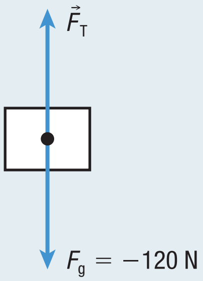


Figure 5

Solution

(a) First draw the FBD of the object. Choose up as positive.



The object is at rest, so it is not accelerating. Newton's first law implies that the net force must be zero.

$$\begin{aligned} \vec{F}_{net} &= \vec{F}_T + \vec{F}_g \\ F_{net} &= F_T + (-120\text{ N}) \\ 0 &= F_T - 120\text{ N} \\ F_T &= +120\text{ N} \end{aligned}$$

The tension in the string is 120 N [up].

(b) In this diagram, the force of gravity has not changed and the object is at rest. This means that the FBD is the same and we will find the same tension. This example reinforces the concept that pulleys only change the direction of force without changing the magnitude of the force.

(c) In this balanced system, both objects are at rest. By drawing an FBD for either object, you will get exactly the same result for the tension. This result is contrary to what most people would expect. Most people would incorrectly say the string is holding up twice as much mass and should have twice the tension. Others incorrectly think the tension is zero since both forces of gravity pull the string at each end and they should cancel. Neither statement is true. The second object is just providing the force necessary to hold up the first object. In other words, the second object is just doing the job of the wall or beam, but otherwise the situation is unchanged.

Sample Problem 2: Objects Connected Horizontally by Strings

Three sleds are tied together and pulled east across an icy surface with an applied force of 120 N [E] (**Figure 6**). The mass of sled 1 is 12.0 kg, the mass of sled 2 is 11.0 kg, and the mass of sled 3 is 7.0 kg. You may assume that no friction acts on the sleds.

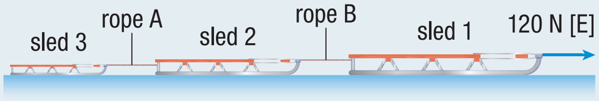


Figure 6

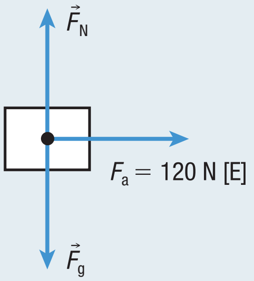
(a) Determine the acceleration of the sleds.

(b) Calculate the magnitude of the tension in rope A.

(c) Calculate the magnitude of the tension in rope B.

Solution

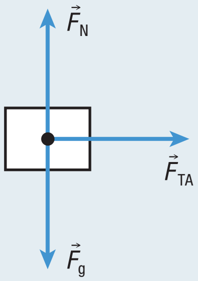
(a) All three sleds will move together with the same acceleration, so we can treat them as one single object. The total mass of all three sleds is $m_T = 12.0\text{ kg} + 11.0\text{ kg} + 7.0\text{ kg} = 30.0\text{ kg}$. There is no need to consider the tension at this point because it is an internal force and will not contribute to the acceleration of the total mass. Choose east as positive. So west is negative.



$$\begin{aligned}\vec{F}_{\text{net}} &= m_T\vec{a}\\ +120\text{ N} &= (30.0\text{ kg})a\\ a &= \frac{+120\text{ N}}{30.0\text{ kg}}\\ a &= +4.0\text{ m/s}^2\end{aligned}$$

The acceleration of all three sleds is 4.0 m/s^2 [E].

(b) We could use the FBD for either sled 2 or sled 3 to calculate the tension in rope A. We will use the FBD for sled 3 because it is slightly simpler—it only has rope A pulling on it, whereas sled 2 has both rope A and rope B pulling on it.



$$\begin{aligned}\vec{F}_{\text{net}} &= \vec{F}_{TA}\\ m_3\vec{a} &= \vec{F}_{TA}\\ (7.0\text{ kg})(+4.0\text{ m/s}^2) &= F_{TA}\\ F_{TA} &= +28\text{ N}\end{aligned}$$

The magnitude of the tension in rope A is 28 N.

(c) To calculate the tension in rope B, we can use the FBD of sled 2, but our answer will depend on the accuracy of the calculated tension in rope A. To avoid this problem, you can either use the FBD of sled 1 or the FBD of sleds 2 and 3 (**Figure 7**). We will choose the latter since it is slightly simpler. In this calculation, we will use a mass of $m_2 + m_3 = 18.0\text{ kg}$.

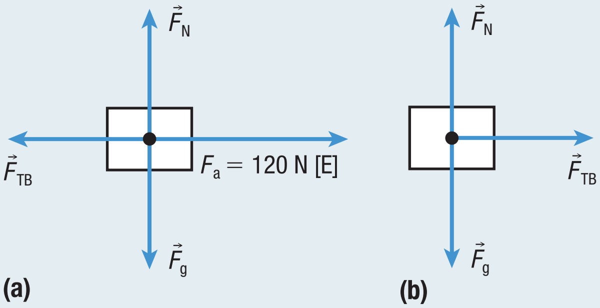


Figure 7 (a) FBD of sled 1 (b) FBD of sleds 2 and 3

$$\begin{aligned}\vec{F}_{\text{net}} &= \vec{F}_{TB}\\ (m_2 + m_3)\vec{a} &= \vec{F}_{TB}\\ (18.0\text{ kg})(+4.0\text{ m/s}^2) &= F_{TB}\\ F_{TB} &= +72\text{ N}\end{aligned}$$

The magnitude of the tension in rope B is 72 N.

Practice

1. Examine each diagram in **Figure 8**. In each situation, which rope will have the greater tension? Explain your reasoning. K/U
2. A locomotive with a mass of 6.4×10^5 kg is accelerating at 0.12 m/s^2 [W] while pulling a train car with a mass of 5.0×10^5 kg. Assume that negligible friction is acting on the train. T/I
   (a) Calculate the net force on the entire train. [ans: 1.4×10^5 N [W]]
   (b) Determine the magnitude of the tension between the locomotive and the train car. [ans: 6.0×10^4 N]

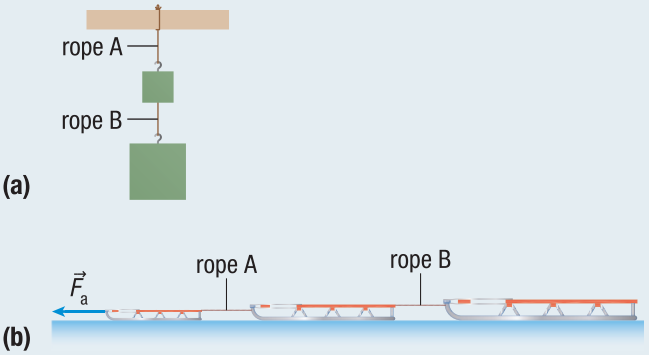


Figure 8

Kinematics and Newton's Laws

When using any of the kinematics equations from Unit 1, it is essential that the acceleration remain constant. Now we can extend this restriction by stating that the net force on an object must also remain constant if you use one of the kinematics equations. This is a direct consequence of Newton's second law, $\vec{F}_{\text{net}} = m\vec{a}$, which shows that net force is constant when the acceleration is constant.

Imagine that you start moving east due to a constant net force acting on you. You might start walking, but you gradually speed up and start running. Then your net force drops to zero and you move at a constant velocity. Finally, another constant net force acts in the opposite direction and slows you down until you eventually come to rest.

During the three separate parts of the trip, your acceleration was constant because the net force was constant. This means that you can use a kinematics equation during one part of the trip but not a single equation for the entire trip. The following Tutorial will clarify how to use kinematics concepts with Newton's laws.

Tutorial 2 Newton's Laws and Kinematics

When solving the following Sample Problems, keep in mind that the acceleration is constant when the net force is constant, according to Newton's second law.

Sample Problem 1: Skater Pushing on the Boards

Starting from rest, an ice skater (54.0 kg) pushes the boards with a force of 130.0 N [W] and moves 0.704 m. He then moves at a constant velocity for 4.00 s before he digs in his skates and starts to slow down. When he digs in his skates, he causes a net force of 38.0 N [W] to slow him down until he stops.

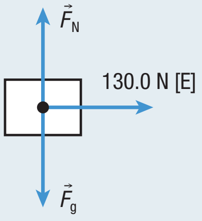
(a) Determine the acceleration of the skater
   (i) when he is pushing on the boards
   (ii) just after he stops pushing on the boards
   (iii) when he starts to slow down

(b) How far does he move?

Solution

Use FBDs to solve this problem.

(a) (i) When the skater pushes the boards with a force of 130.0 N [W], the boards push back on the skater with an equal and opposite force of 130.0 N [E]. Choose east as positive. So west is negative.



$$\vec{F}_{\text{net}} = m\vec{a}$$

$$+130.0\text{ N} = (54.0\text{ kg})a$$

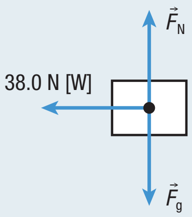
$$a = \frac{+130.0\text{ N}}{54.0\text{ kg}}$$

$$a = 2.407\text{ m/s}^2 \text{ (one extra digit carried)}$$

The acceleration of the skater is 2.41 m/s² [E] when he is pushing on the boards.

(ii) When he stops pushing on the boards, the net force acting on him is zero. According to Newton's first law, his acceleration will also be zero.

(iii) Now the skater is slowing down and the net force is opposite to the direction of motion.



$$\vec{F}_{\text{net}} = m\vec{a}$$

$$-38.0\text{ N} = (54.0\text{ kg})a$$

$$a = \frac{-38.0\text{ N}}{54.0\text{ kg}}$$

$$a = -0.704\text{ m/s}^2$$

The acceleration of the skater is 0.704 m/s² [W] when he is slowing down.

(b) During part (i), the skater moves 0.704 m [E], but we need to calculate his final velocity in order to calculate his displacement during the other sections of the motion.

Given: $\vec{v}_1 = 0$; $\Delta\vec{d} = 0.704\text{ m [E]}$; $\vec{a} = 2.407\text{ m/s}^2\text{ [E]}$

Required: $\vec{v}_2$

Analysis: $v_2^2 = v_1^2 + 2a\Delta d$

Solution: $v_2^2 = v_1^2 + 2a\Delta d$

$$v_2^2 = (0)^2 + 2(+2.407\text{ m/s}^2)(+0.704\text{ m})$$

$$v_2 = 1.841\text{ m/s (one extra digit carried)}$$

Now we can calculate the displacement for the other sections of the motion. For part (ii),

$$\Delta\vec{d} = \vec{v}\Delta t$$

$$= (+1.841\text{ m/s})(4.00\text{ s})$$

$$\Delta d = 7.364\text{ m (one extra digit carried)}$$

For part (iii),

$$v_2^2 = v_1^2 + 2a\Delta d$$

$$0^2 = (+1.841\text{ m/s})^2 + 2(-0.704\text{ m/s}^2)\Delta d$$

$$\Delta d = 1.981\text{ m (one extra digit carried)}$$

Statement: The total distance travelled by the skater is $0.704\text{ m} + 7.364\text{ m} + 1.981\text{ m} = 10.1\text{ m}$

Sample Problem 2

A worker pushes two large boxes across the floor from rest with an applied force of 160.0 N [right] on the larger box (**Figure 9**). The boxes are touching. The mass of the larger box is $m_1 = 32.0$ kg and the mass of the smaller box is $m_2 = 8.0$ kg. The force of friction on the large box is 80.0 N [left] and the force of friction on the smaller box is 20.0 N [left].

(a) Calculate the acceleration of the two boxes. Assume that the boxes start to move.
(b) Determine the force exerted by the larger box on the smaller box.
(c) Determine the velocity of the boxes after 4.0 s.

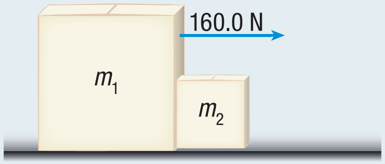
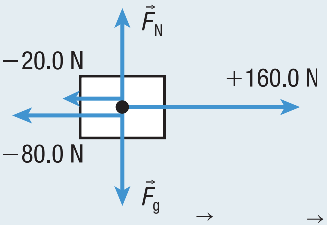


Figure 9

(a) Both boxes must move together with the same acceleration, so for now we will treat them like one single object with a total mass of $m_T = 32.0\text{ kg} + 8.0\text{ kg} = 40.0$ kg. From the FBD for both boxes, the normal force and gravity cancel. Choose right as positive. So left is negative.



$$\vec{F}_{net} = m_T\vec{a}$$

$$+160.0\text{ N} + (-80.0\text{ N}) + (-20.0\text{ N}) = m_T a$$

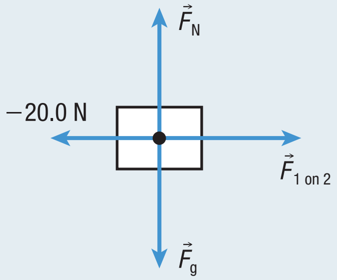
$$+60.0\text{ N} = (40.0\text{ kg})a$$

$$a = \frac{+60.0\text{ N}}{40.0\text{ kg}}$$

$$= +1.5\text{ m/s}^2$$

The acceleration of both boxes is 1.5 m/s² [right].

(b) The force from the large box on the smaller box is an internal force. To calculate this force, we need to draw the FBD for just one box. Either box will do but we will use the smaller one because it has fewer forces acting on it. Again, the normal force and the force of gravity cancel.



$$F_{net} = F_{1\text{ on }2} + (-20.0\text{ N})$$

$$m_2 a = F_{1\text{ on }2} - 20.0\text{ N}$$

$$(8.0\text{ kg})(+1.5\text{ m/s}^2) = F_{1\text{ on }2} - 20.0\text{ N}$$

$$F_{1\text{ on }2} = +32.0\text{ N}$$

The force exerted by the larger box on the smaller box is 32.0 N [right].

(c) **Given:** $\vec{v}_1 = 0$; $\Delta t = 4.0$ s; $\vec{a} = 1.5\text{ m/s}^2$ [right]

Required: $\vec{v}_2$

Analysis: $\vec{v}_2 = \vec{v}_1 + \vec{a}\Delta t$

Solution: $\vec{v}_2 = \vec{v}_1 + \vec{a}\Delta t$

$$= 0 + (+1.5\text{ m/s}^2)(4.0\text{ s})$$

$$v_2 = +6.0\text{ m/s}$$

Statement: The final velocity of both boxes is 6.0 m/s [right].

Practice

1. Two dynamics carts are placed end to end. Cart 1 (1.2 kg) is stuck to cart 2 (1.8 kg). Cart 1 is pushed with a force of 18.9 N [W], causing cart 1 to push cart 2 forward. Ignore the force of friction. T/I
   (a) Calculate the acceleration of each cart. [ans: 6.3 m/s² [W]]
   (b) Calculate the force that cart 1 exerts on cart 2. [ans: 11 N [W]]
   (c) Would your answers change if cart 2 were pushed with an equal but opposite force instead of cart 1? If your answers change, calculate the new results. [ans: 6.3 m/s² [E]; 7.6 N [W]]
2. A 1200 kg car is moving at 95 km/h when the driver notices a deer down the road. He immediately moves his foot toward the brake pedal, taking only 0.50 s before the car starts slowing down. The brakes cause a net force of 2400 N [backwards] on the car for 2.0 s. The deer then jumps out of the way and the driver lifts his foot off the brake pedal. How far does the car move in the 2.5 s starting from when the driver sees the deer? T/I [ans: 62 m]

3.5 Summary

- The tensions at both ends of a string or a rope are equal in magnitude.
- Tension can be measured with a spring scale or a force sensor.
- The key equations of motion from the Kinematics unit and Newton's laws can be used together to solve motion problems.

3.5 Questions

1. You hold one end of a rope and pull horizontally with a force of 65 N. Calculate the tension in the rope if the other end is
   (a) tied to a wall
   (b) held by a friend who pulls with 65 N in the opposite direction
   (c) tied to a 12 kg object on smooth ice T/I
2. A 72 kg sled is pulled forward from rest by a snowmobile and accelerates at 2.0 m/s^2 [forward] for 5.0 s. The force of friction acting on the sled is 120 N [backwards]. The total mass of the snowmobile and driver is 450 kg. The drag force acting on the snowmobile is 540 N [backwards]. T/I
   (a) Determine the tension in the rope.
   (b) Calculate the force exerted by the snowmobile that pushes the sled forward.
3. Two people, each with a mass of 70 kg, are wearing inline skates and are holding opposite ends of a 15 m rope. One person pulls forward on the rope by moving hand over hand and gradually reeling in more of the rope. In doing so, he exerts a force of 35 N [backwards] on the rope. This causes him to accelerate toward the other person. Assuming that the friction acting on the skaters is negligible, how long will it take for them to meet? Explain your reasoning. T/I
4. A 1200 kg car pulls an 820 kg trailer over a rough road. The force of friction acting on the trailer is 650 N [backwards]. Calculate the force that the car exerts on the trailer if
   (a) the trailer is moving at a constant velocity of 30 km/h [forward]
   (b) the trailer is moving at a constant velocity of 60 km/h [forward]
   (c) the trailer is moving forward at 60 km/h and starts accelerating at 1.5 m/s^2 [forward]
   (d) the trailer is moving forward at 60 km/h and starts accelerating at 1.2 m/s^2 [backwards] T/I
5. An old rope can now only safely suspend 120 kg. When the rope is tied to a beam, it hangs down with a vertical length of 12.0 m. Calculate the minimum time required for an 85 kg person starting from rest to climb the entire length of the rope without breaking it. T/I
6. Three dynamics carts have force sensors placed on top of them. Each force sensor is tied to a string that connects all three carts together (**Figure 10**). You use a sixth force sensor to pull the three dynamics carts forward. The reading on force sensor 2 is 3.3 N. Assume that the force sensors are light and that there is negligible friction acting on the carts. T/I

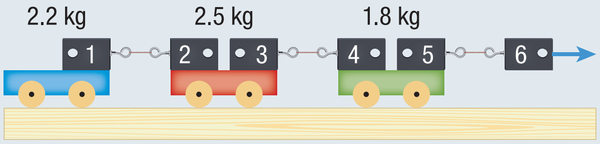


Figure 10

   (a) What is the acceleration of all the carts?
   (b) What is the reading on each force sensor?
   (c) What force are you applying to force sensor 6?
7. A locomotive (6.4×10^5 kg) is used to pull two railway cars (**Figure 11**). Railway car 1 (5.0×10^5 kg) is attached to railway car 2 (3.6×10^5 kg) by a locking mechanism. A railway engineer tests the mechanism and estimates that it can only withstand 2.0×10^5 N of force. Determine the maximum acceleration of the train that does not break the locking mechanism. Explain your reasoning. Assume that friction is negligible. T/I C

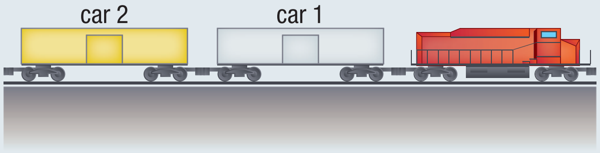


Figure 11

8. A skier (68 kg) starts from rest but then begins to move downhill with a net force of 92 N for 8.2 s. The hill levels out for 3.5 s. On this part of the hill, the net force on the skier is 22 N [backwards]. T/I
   (a) Calculate the speed of the skier after 8.2 s.
   (b) Calculate the speed of the skier at the end of the section where the hill levels out.
   (c) Calculate the total distance travelled by the skier before coming to rest.

Galileo, Newton, and Hawking

ABSTRACT
In his book *Principia Mathematica,* Newton realized that the laws governing the motion of planets could be applied to all physical phenomena. Newton's predictions have had an impact on many fields of science and technology. Einstein's theory of relativity and Stephen Hawking's work on the nature of gravity and black holes are grounded in Newton's laws. Newton's work in *Principia Mathematica* may be the greatest achievement in physics.

On July 5, 1687, Newton (**Figure 1**) first published his landmark book *Principia Mathematica*. This work consisted of three volumes and included many mathematical discoveries, as well as his famous laws of motion. He also used some of Galileo's earlier work to help formulate some of his own ideas, such as the concept of inertia.

The primary focus of *Principia Mathematica* is on massive objects in motion, such as planets in our solar system. Newton realized that the rules governing the motion of large objects in the universe could be used to study how other fundamental forces act on objects.

In Newton's time, the other fundamental forces were either not well understood (such as electromagnetic force) or completely unknown (such as the strong and weak nuclear forces). Yet in *Principia Mathematica*, Newton predicted that the laws of physics would somehow be able to account for all physical phenomena.

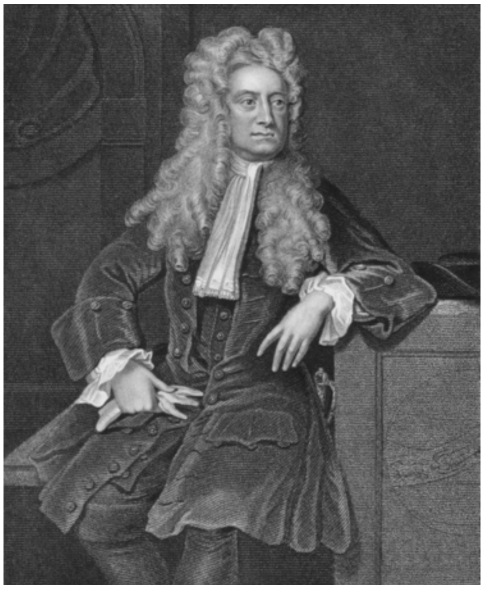


Figure 1 Isaac Newton

Newton and the Foundations of Physics

Today we know that not only was Newton on the right track with his prediction, but his discoveries have had impacts on fields of study and technology that no one could have predicted in Newton's time. His laws of motion and his ideas about gravity are used to construct buildings and bridges, design cars and planes, and launch satellites into orbit.

Newton's laws of motion are also the foundation of physics wherever forces are a factor. Albert Einstein wrote, "To the Master's honour all must turn, each in its track, without a sound, forever tracing Newton's ground." This is an eloquent way of stating that Newton's laws of motion are so all-inclusive that any other endeavour in physics can be traced back in some way to Newton's work.

Einstein: Extending Newton's Ideas

Einstein's work on relativity followed a path very similar to Newton's laws. Einstein's special theory of relativity extended Newton's first law to deal with the special case of objects moving at a very fast, constant velocity. Einstein's theory of general relativity extended Newton's second and third laws to deal with accelerating objects and gravity.

Newton's third law deals with action and reaction forces. The most obvious example of these is contact forces. If you push on an object, it will push back on you with an equal but opposite force. Newton also stated that this was true of gravity, which is an action-at-a-distance force. For example, when you jump up into the air, the force of gravity exerted by Earth pulls you back down. There is also a reaction force on Earth exerted by you, pulling up on Earth.

What about the other action-at-a-distance forces? Does Newton's third law still apply to those forces? For example, when a positive charge exerts a force on another charge, is there an equal and opposite reaction force? What about magnetism? When a north pole of one magnet exerts a force on a north pole of another magnet, is there also a reaction force? This is what Newton was thinking about in the preface of *Principia Mathematica*. The answer to all of these questions is yes. Newton's third law works for any action-at-a-distance force, as well as any contact force. This makes the third law even more general and all-encompassing than he had imagined.

Stephen Hawking: Standing on the Shoulders of Giants

Physicist Stephen Hawking has continued with the work started by Galileo, Newton, and Einstein (**Figure 2**) in his study of the universe. His work deals mainly with extending the concepts explored by Newton and Einstein to topics such as black holes and the nature of gravity. One of his most widely known accomplishments is the idea that even black holes can lose mass through Hawking radiation (**Figure 3**).

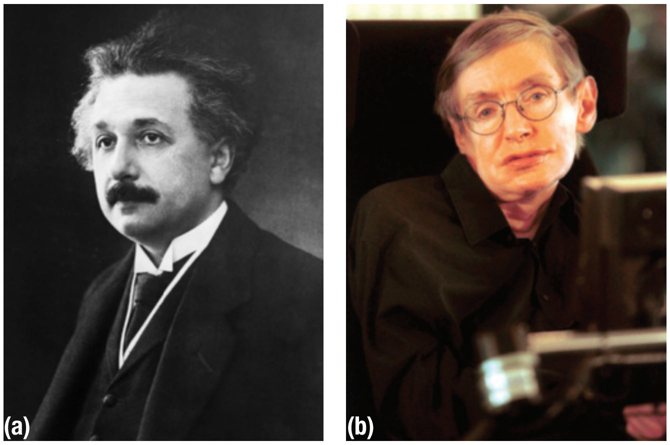


Figure 2 (a) Albert Einstein (b) Stephen Hawking

To put the contributions and accomplishments of Newton into perspective, Hawking wrote,

> Einstein is the only figure in the physical sciences with a stature that can be compared with Newton. Newton is reported to have said: "If I have seen further than other men, it is because I stood on the shoulders of giants." This remark is even more true of Einstein who stood on the shoulders of Newton. Both Newton and Einstein put forward a theory of mechanics and a theory of gravity but Einstein was able to base General Relativity on the mathematical theory of curved spaces that had been constructed by Riemann while Newton had to develop his own mathematical machinery. It is therefore appropriate to acclaim Newton as the greatest figure in mathematical physics and the *Principia* is his greatest achievement.

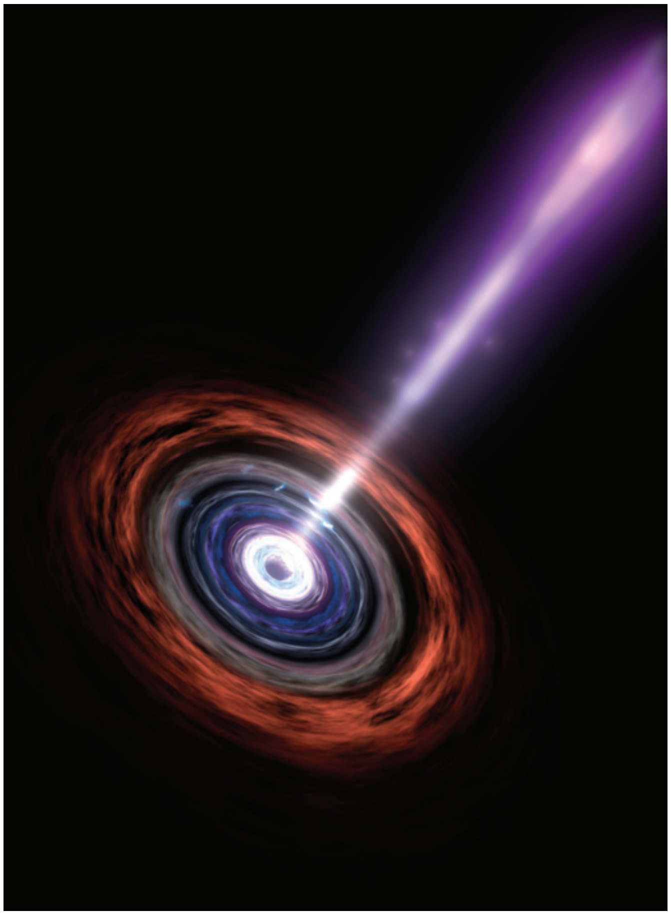


Figure 3 Hawking radiation from a black hole. Until Hawking showed otherwise, people thought that nothing could escape a black hole.

Further Reading

Greene, B. (1999). *The Elegant Universe*. New York: W. W. Norton & Company.

Hawking, S. (1988). *A Brief History of Time*. New York: Bantam Dell.

Hawking, S. (2001). *The Universe in a Nutshell*. New York: Bantam Books.

Hawking, S., & Israel, W. (Eds.). (1987). *300 Years of Gravitation*. New York: Cambridge.

3.6 Questions

1. Explain the meaning of the statement, "Great physicists are often influenced by the great physicists of the past." K/U C
2. Describe, using an example, how Newton's laws of motion have affected your own life. C A
3. Explain why Hawking places Newton ahead of Einstein as the greatest figure in mathematical physics. K/U C
4. Research some of the other topics and concepts covered in *Principia Mathematica* not outlined in this section. For one of these topics, write a short report on its significance and applications. T/I C A

GO TO NELSON SCIENCE

Investigation 3.3.1 CONTROLLED EXPERIMENT

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Investigating Newton's Second Law

In this investigation, you will perform two controlled experiments. In Part A, you will measure the acceleration of a cart using different net forces while keeping the total mass constant. In Part B, you will measure the acceleration of a cart using different total masses while keeping the net force constant.

Testable Questions

- How does the acceleration of a cart depend on the net force acting on the cart if the total mass is constant?
- How does the acceleration of a cart depend on the total mass if the net force is constant?

Hypothesis/Prediction

SKILLS HANDBOOK A2.2

After reading through the experiment, write a hypothesis to answer each Testable Question.

Variables

Identify the independent (sometimes called manipulated) and dependent (sometimes called responding) variables in this experiment. Describe how you will measure these variables. What variables must be controlled?

Experimental Design

There are many different ways to perform this activity. **Figure 1** shows one simple way to apply a constant force to a cart.

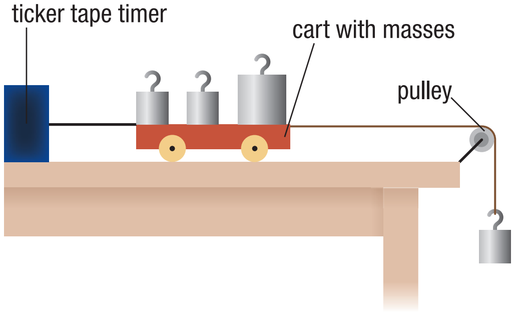


Figure 1

Keep in mind that the force of gravity acting on the hanging object is the net force on the total mass. The total mass includes the hanging object, the cart, the string, and any objects on top of the cart. If you want to change the force and keep the total mass constant, take an object off the cart and hang it from the string. If you want to change the mass and keep the net force constant, change the objects on top of the cart but do not change the hanging objects.

Discuss with your group members how you will safely stop the cart before performing the investigation.

Equipment and Materials

- dynamics cart
- electronic balance
- ticker tape timer, motion sensor, or similar device
- three 100 g objects
- three 1.0 kg objects
- pulley
- string
- ticker tape

Procedure

Part A: Acceleration and Net Force

1. Create a table to record your observations similar to **Table 1**.

Table 1

Total mass	Hanging mass	Net force	Acceleration	Net force/ total mass

2. Measure the mass of the cart.
3. Set up the equipment as shown in Figure 1 or as directed by your teacher. Make sure everything is working properly by allowing the cart to accelerate once or twice.
4. Put one 1.0 kg object and two 100 g objects on top of the cart. You might need to tape them down. Hang a 100 g object from the string. Allow the motion to occur and obtain the data required to find the acceleration ($\vec{a}_1$).
5. Take one of the 100 g objects from on top of the cart and hang it from the string. Allow the motion to occur and obtain the data required to find the new acceleration ($\vec{a}_2$).
6. Take the last 100 g object from the top of the cart and hang it from the string. Allow the motion to occur and obtain the data required to find the new acceleration ($\vec{a}_3$).

Part B: Acceleration and Mass

7. Use the data for $\vec{a}_3$ from Step 6 as the first set of data for this experiment.
8. Using the same cart setup as in Step 6, add one 1.0 kg object to the cart. Allow the motion to occur and obtain the data required to find the new acceleration ($\vec{a}_4$).
9. Add an additional 1.0 kg object to the cart. Allow the motion to occur and obtain the data required to find the new acceleration ($\vec{a}_5$).

Analyze and Evaluate

(a) In terms of the variables in this investigation, what type of relationship was being tested? T/I

(b) Calculate the acceleration for each trial. T/I

(c) Calculate the ratio of the net force to the total mass. What does this ratio represent? Explain your reasoning. K/U T/I

(d) Use your results from Part A to plot a graph of net force (y-axis) versus acceleration (x-axis). Draw a line of best fit and calculate its slope. What does this graph indicate about the relationship between acceleration and net force? What does the slope represent? T/I C

(e) Use your results from Part B to plot a graph of acceleration (y-axis) versus total mass (x-axis). Draw a smooth curve through the points. What does this graph indicate about the relationship between acceleration and total mass? T/I C

(f) Use your results from Part B to plot a graph of acceleration (y-axis) versus the reciprocal of the total mass ($1/m$; x-axis). Draw a line of best fit and calculate its slope. What does this graph indicate about the relationship between acceleration and total mass? What does the slope represent? T/I C

(g) Answer the Testable Questions. T/I

(h) Comment on the accuracy of your hypothesis. C

(i) List some possible sources of error. How could you modify the investigation to avoid or reduce these sources of error? T/I

Apply and Extend

(j) Describe how you could determine if friction had any effect on the results of this investigation. T/I

(k) Explain why a graph of net force versus acceleration must pass through the origin when the total mass is constant. T/I

(l) Explain why a graph of acceleration versus the reciprocal of the total mass must pass through the origin when net force is constant. T/I

(m) Commercial airlines are limiting the number of pieces and the mass of luggage that passengers can bring onto an aircraft. Use what you have learned in this investigation to explain why. C A

CHAPTER 3 SUMMARY

Summary Questions

1. Create a study guide for this chapter based on the Key Concepts listed in the margin on page 112. For each point, create three or four subpoints that provide further information, relevant examples, explanatory diagrams, or general equations.
2. Look back at the Starting Points questions on page 112. Answer these questions using what you have learned in this chapter. Compare your latest answers with those that you wrote at the beginning of the chapter. Note how your answers have changed.
3. You may use several different forms of active transportation, such as bicycles, skateboards, and inline skates. Using the concepts of this chapter, analyze the safety issues of one of these forms of transportation. Make sure you use all of Newton's laws in your explanations. Also provide some safety tips that will help reduce the chance of serious injury.

Vocabulary

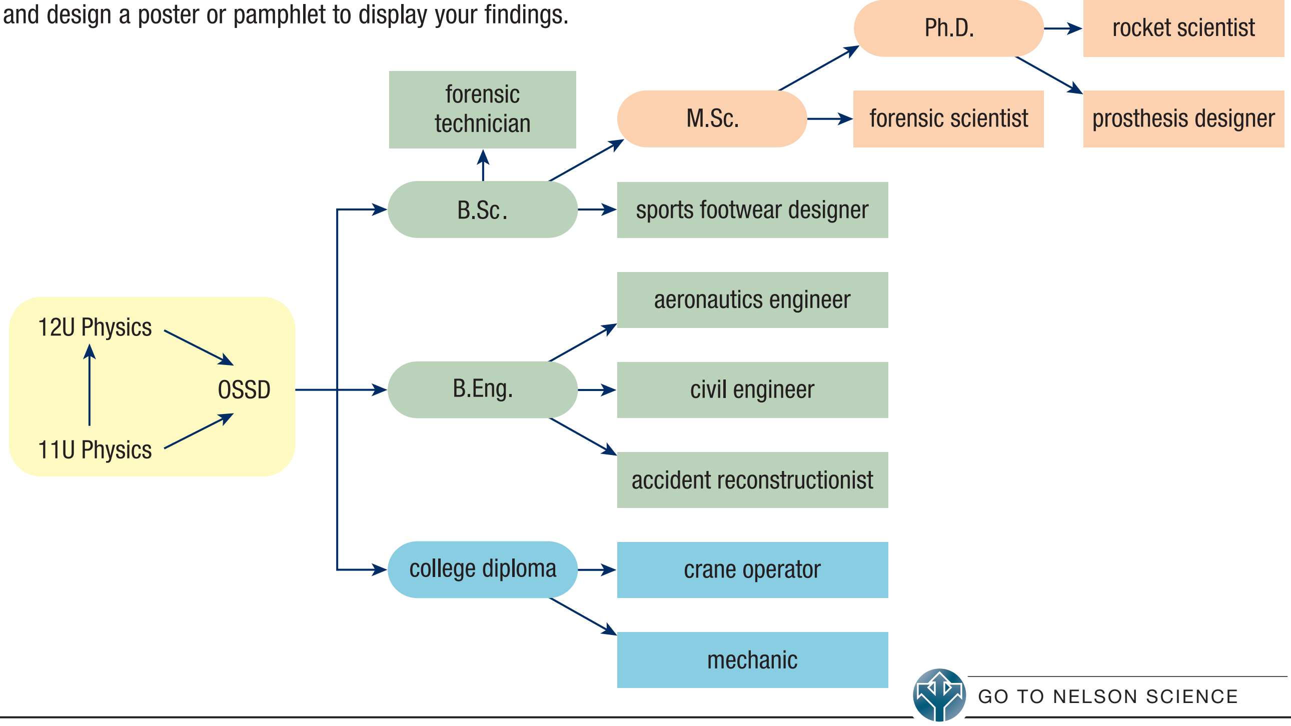
dynamics (p. 114)
newton (N) (p. 114)
system diagram (p. 114)
free-body diagram (FBD) (p. 115)
applied force ($\vec{F}_a$) (p. 115)
tension ($\vec{F}_T$) (p. 115)
normal force ($\vec{F}_N$) (p. 115)
friction ($\vec{F}_f$) (p. 115)
force of gravity ($\vec{F}_g$) (p. 116)
net force ($\vec{F}_{net}$) (p. 119)
inertia (p. 124)
first law of motion (p. 124)
second law of motion (p. 131)
third law of motion (p. 137)

CAREER PATHWAYS

Grade 11 Physics can lead to a wide range of careers. Some require a college diploma or a bachelor of science degree. Others require specialized or post-graduate degrees. This graphic organizer shows a few pathways to careers related to topics covered in this chapter.

SKILLS HANDBOOK A7

1. Select an interesting career that relates to forces and Newton's laws of motion. Research the educational pathway you would need to follow to pursue this career.
2. What is involved in the career you have chosen? Research at least two programs, and design a poster or pamphlet to display your findings.



materials scientist
Ph.D.
rocket scientist
forensic technician
M.Sc.
forensic scientist
prosthesis designer
B.Sc.
sports footwear designer
aeronautics engineer
12U Physics
OSSD
B.Eng.
civil engineer
11U Physics
accident reconstructionist
college diploma
crane operator
mechanic

GO TO NELSON SCIENCE

CHAPTER 3 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. Which of the following best describes a normal force? (3.1) K/U
   (a) a force that resists the motion or attempted motion of an object
   (b) a perpendicular force exerted by a surface on an object in contact with the surface
   (c) the pull between two objects at a distance
   (d) the force in a string or rope when pulled
2. Which force is responsible for the interactions during particle transformations? (3.1) K/U
   (a) electromagnetic
   (b) gravitational
   (c) weak nuclear
   (d) strong nuclear
3. Which object, when stationary, has the least inertia? (3.2) K/U
   (a) a desk
   (b) a pen
   (c) a computer
   (d) a feather
4. A 60.0 kg object accelerates with a magnitude of 2.0 m/s^2. What is the magnitude of the net force acting on this object? (3.3) T/I
   (a) 30 N
   (b) 60 N
   (c) 120 N
   (d) 180 N
5. What is the mass of a rock that experiences a gravitational force of magnitude 11.8 N? (3.1) T/I
   (a) 1.1 kg
   (b) 1.3 kg
   (c) 1.2 kg
   (d) 1.0 kg
6. Which statement best describes Newton's third law? (3.4) K/U
   (a) For every action force, there is a reaction force of lesser magnitude and in the same direction.
   (b) For every action force, there is a reaction force of equal magnitude but opposite in direction.
   (c) For every action force, there is a reaction force of equal magnitude and in the same direction.
   (d) For every action force, there is a reaction force of lesser magnitude but in the opposite direction.
7. An ice skater pushes off a railing. Which of the following is the reaction force? (3.4) K/U
   (a) the force of the skater pushing off the railing
   (b) the force of the railing pushing back on the skater
   (c) the force of friction from the ice
   (d) the force of gravity
8. What important realization did Newton describe in *Principia Mathematica?* (3.6) K/U
   (a) Forces are governed by the theory of relativity.
   (b) The rules governing the motion of large objects in the universe can be used to study how fundamental forces act on objects.
   (c) Black holes lose mass through a special type of radiation.
   (d) Apples fall from trees due to gravitational force.

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

9. Forces are measured in newtons. (3.1) K/U
10. The normal force is the force resisting the motion or attempted motion of an object. (3.1) K/U
11. A free-body diagram is a simple sketch of all the objects involved in a situation. (3.1) K/U
12. All forces require objects to be in contact and cannot act at a distance. (3.1) K/U
13. The net force on an object is the sum of all the forces acting on it. (3.1) K/U
14. Massive objects have more inertia than less massive objects. (3.2) K/U
15. An object can change its motion even if the net force acting on it is zero. (3.2) K/U
16. If the net force on an object is constant and the mass decreases, then the acceleration increases. (3.3) K/U
17. Newton's third law states that for every action force, there is a simultaneous reaction force of equal magnitude acting in the same direction. (3.4) K/U

To do an online self-quiz,

GO TO NELSON SCIENCE

CHAPTER 3 REVIEW

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

Knowledge

For each question, select the best answer from the four alternatives.

1. Which of the following symbols is used for a tension force? (3.1) K/U
   (a) $\vec{F}_{\text{a}}$
   (b) $\vec{F}_{\text{net}}$
   (c) $\vec{F}_{\text{T}}$
   (d) $\vec{F}_{\text{f}}$
2. In which direction does friction act? (3.1) K/U
   (a) parallel to the surface and opposite to an object's motion or attempted motion
   (b) perpendicular to the surface and opposite to an object's motion or attempted motion
   (c) parallel to the surface and in the same direction as an object's motion or attempted motion
   (d) normal to the surface and opposite to an object's motion or attempted motion
3. Which of the following symbols is used to represent the sum of all forces acting on an object? (3.1) K/U
   (a) $\vec{F}_{\text{N}}$
   (b) $\vec{F}_{\text{a}}$
   (c) $\vec{F}_{\text{T}}$
   (d) $\vec{F}_{\text{net}}$
4. Which force holds the protons together in the nucleus of an atom? (3.1) K/U
   (a) electromagnetic
   (b) gravitational
   (c) weak nuclear
   (d) strong nuclear
5. You have your seat belt on in the passenger seat of a car. The car suddenly accelerates. Which statement best describes your motion? (3.2) K/U
   (a) Your body will suddenly move forward with respect to the seat.
   (b) Your head will suddenly move forward with respect to your body.
   (c) Both your body and your head will move forward at the same rate.
   (d) Your head and your body will suddenly move backwards with respect to the seat.
6. Which of the following correctly states Newton's second law? (3.3) K/U
   (a) $\vec{F}_{\text{net}} = \dfrac{\vec{a}}{m}$
   (b) $m\vec{F}_{\text{net}} = \vec{a}$
   (c) $\vec{F}_{\text{net}} = m\vec{a}$
   (d) $\vec{F}_{\text{net}} < m\vec{a}$
7. A boy jumps off a skateboard. What is the reaction force? (3.4) K/U
   (a) the force exerted by the boy pushing off the skateboard
   (b) the force exerted by the skateboard pushing back on the boy
   (c) the force of friction exerted by the road on the skateboard
   (d) the force of gravity causing the boy to land on the ground
8. Which device could be used to measure tension? (3.5) K/U
   (a) a bathroom scale
   (b) a balance
   (c) a spring scale
   (d) a sliding scale

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

9. One newton is equal to 1 kg·m/s. (3.1) K/U
10. A tension force is a perpendicular force acting on an object that is exerted by the surface with which it is in contact. (3.1) K/U
11. Friction is a force that resists the motion or attempted motion of an object. (3.1) K/U
12. Forces that do not require contact are called action-at-a-distance forces. (3.1) K/U
13. To determine the net force, you do not need to consider the direction of each force acting on an object. (3.1) K/U
14. An object with less mass has more inertia. (3.2) K/U
15. If there is a net force acting on an object, then the motion of the object will change. (3.2) K/U
16. If the net force on an object is constant and the mass increases, then the acceleration decreases. (3.3) K/U
17. Newton's third law states that for every action force there is a simultaneous reaction force of lesser magnitude in the opposite direction. (3.4) K/U

Match each term on the left with the most appropriate description on the right.

18.	(a) weak nuclear	(i)	a pulling force from a rope or a string
	(b) normal	(ii)	a force that resists the motion or attempted motion of an object
	(c) friction	(iii)	the force responsible for interactions during particle transformations
	(d) tension	(iv)	the force of attraction between two objects because of their mass
	(e) gravity	(v)	a perpendicular force exerted by a surface on an object (3.1) K/U

Write a short answer to each question.

19. What is the rate of acceleration due to gravity? (3.1) K/U
20. In your own words, describe what it means for an object to have inertia. (3.2) K/U C
21. In your own words, describe Newton's third law and give an example that demonstrates this law. (3.4) K/U C

Understanding

22. A book sits on a desk. Draw a free-body diagram of all the forces acting on the book. (3.1) K/U
23. The free-body diagram in **Figure 1** represents a block being dragged at constant velocity across a rough surface. Copy Figure 1 into your notebook and draw in the missing force vector. Be sure to indicate its direction and magnitude relative to the other forces shown. (3.1) K/U

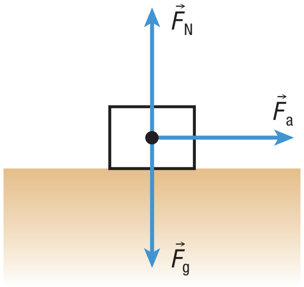


Figure 1

24. The free-body diagram in **Figure 2** represents a block sitting motionless on a ramp. Is the FBD complete? Explain. Include an FBD in your answer. (3.1) T/I C

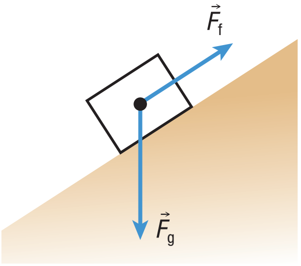


Figure 2

25. Draw a free-body diagram for the first two situations. Then answer (c). (3.1) T/I C
    (a) A student pulls a large box across a smooth floor to the right.
    (b) A student pushes a large box across a smooth floor to the right.
    (c) Are there any differences between your diagrams for (a) and (b)? Explain.
26. The engines of a plane exert a horizontal force of magnitude 37 850 N while the plane is flying northward. A wind blowing to the south also exerts a horizontal force of magnitude 850 N on the plane. What is the net horizontal force on the plane? (3.1) T/I
27. The engines of a plane flying westward exert a horizontal force of magnitude 35 000 N. A wind blowing westward exerts a horizontal force of magnitude 1200 N. What is the net horizontal force on the plane? (3.1) T/I
28. A trap door that opens in the middle is stuck half open with a box sitting on it (**Figure 3**). Draw a free-body diagram for the box. (3.1) T/I

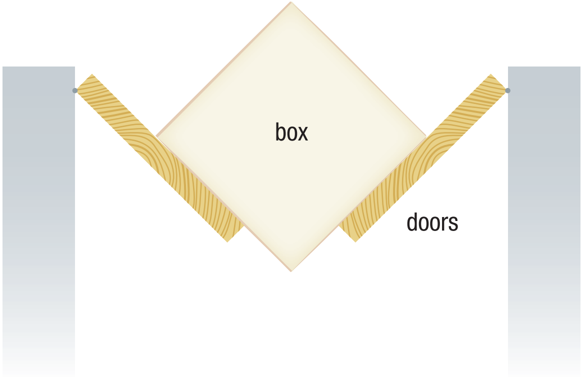


Figure 3

29. Use Newton's first law to explain why the normal force must be equal in magnitude to the force of gravity for an object to remain at rest on a horizontal surface when no other forces are acting on the object. (3.2) K/U C

30. Four children are playing tug-of-war. The two children on the right pull with forces of magnitude 84 N and 86 N, and one of the children on the left is able to pull with a force of magnitude 83 N. If the rope remains stationary, how hard is the second child on the left pulling? (3.2) T/I

31. A student is trying to push a box across the floor with 20 N of force, but the box does not move. What is the magnitude of the frictional force exerted by the ground on the box? (3.2) T/I

32. Answer each question below using Newton's second law. Explain your answers. (3.3) K/U C
    (a) Two cars have the same net force acting on them, but one has more mass than the other. Which car will have the greater acceleration?
    (b) A heavy box of sand is on top of a cart. A person pulls the cart forward with a constant net force while the sand leaks out of the box and onto the ground. What will happen to the acceleration of the cart?

33. Calculate the net force in each situation. (3.3) T/I
    (a) A 69 kg sprinter accelerates at 2.1 m/s^2 [forward].
    (b) A 620 g basketball falls through the net.

34. Calculate the net acceleration in each situation. (3.3) T/I
    (a) A 260 kg boat crew paddles north with a net force of magnitude 468 N.
    (b) A 70.0 kg skydiver opens his parachute and experiences a net force of 236 N [up].

35. A student pushes a 10 kg box and lets it slide across the floor. The magnitude of the frictional force acting on the box is 40 N. What is the acceleration of the box? (3.3) T/I

36. A 175 g hockey puck slows down at a rate of 1.5 m/s^2 as it slides across the ice. Determine the frictional force acting on the puck. (3.3) T/I

37. The engines of an airplane exert a net force of magnitude 800 000 N during takeoff, causing the plane to accelerate at a rate of 8.0 m/s^2 [forward]. What is the mass of the plane? (3.3) T/I

38. A batter hits a baseball with a mass of 145 g. After impact, the ball experiences a net force of 1.80×10^3 N [S]. What is the acceleration of the ball? (3.3) T/I

39. The cart in **Figure 4** has a mass of 2.3 kg and is attached to a 1.7 kg object. Calculate the acceleration of the cart given the following assumptions: (3.3) T/I
    (a) The force of friction is negligible.
    (b) The frictional force acting on the wheels of the cart has a magnitude of 0.6 N.

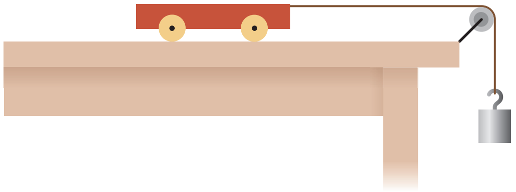


Figure 4

40. Assume the cart in Figure 4 has an acceleration of magnitude 2.5 m/s^2 and a mass of 1.8 kg. Calculate the mass of the attached object given the following assumptions: (3.3) T/I
    (a) The force of friction is negligible.
    (b) A frictional force of magnitude 0.4 N acts on the wheels of the cart.

41. Explain each situation using Newton's third law. (3.4) K/U
    (a) A boat is able to float on water.
    (b) A dolphin can jump out of the water by pushing down on the water.
    (c) A raft glides to the left when a student jumps off the raft to the right.

42. When a cannon fires, it rolls backwards. Use your knowledge of Newton's laws to explain why this happens. (3.4) K/U C

43. A student stands on a skateboard and pushes on a wall with a force of magnitude 89 N. The total mass of the student and the skateboard is 58 kg. Assume that the force of friction is negligible. (3.4) T/I C
    (a) Calculate the acceleration of the student.
    (b) Explain why the wall does not appear to move.

44. A girl is ice skating and pushes off a rail with a force of magnitude 75 N. The total mass of the girl and her skates is 62 kg. (3.4) T/I C
    (a) Calculate the acceleration of the girl while she is pushing if the ice exerts a frictional force of magnitude 4.0 N on the skates.
    (b) Explain why the rail does not appear to move.

45. A 3.0 kg object hangs from a string inside an elevator. Calculate the tension in the string for the following situations. (3.5) T/I
    (a) The elevator is stationary.
    (b) The elevator is accelerating at 1.2 m/s^2 [up].
    (c) The elevator is accelerating at 1.4 m/s^2 [down].

Analysis and Application

46. Wind is blowing a flag to the east. What other forces are acting on the flag if it remains attached to a pole? Include an FBD of the flag in your answer. (3.1, 3.2) T/I

47. A skydiver has a mass of 71.5 kg. What is the force of gravity acting on him
    (a) when he jumps?
    (b) after he has landed? (3.1) T/I

48. A 45.0 kg girl is sitting on a bench. What is the magnitude of the force with which the bench pushes against the girl? (3.1, 3.4) K/U

49. A boulder rolls off the edge of a cliff and initially falls with a force of magnitude 1100 N. What is the mass of the boulder? (3.1) K/U

50. A student weighs out 7.6 N of water into a beaker. What is the mass of the water? (3.1) K/U

51. A T-shirt launcher is capable of shooting shirts at 35 m/s horizontally. If the time it takes to accelerate the shirts to this speed is 0.50 s and each shirt has a mass of 250 g, how much force does the launcher exert on the shirts? Assume that the friction in the tube is negligible. (3.3) T/I

52. A 72 kg runner is jogging at a rate of 6.0 m/s and then begins to sprint, reaching a full speed of 15 m/s after 3.0 s. What is the net force acting on the runner? (3.3) T/I

53. Two boxes of mass 30.0 kg and 10.0 kg are at rest side by side (**Figure 5**). You apply a force of 3.0×10^2 N on the first box for 5.0 s, and they both slide across the floor. The larger box has a force of friction of 180 N, and the smaller box has a force of friction of 60.0 N. (3.3, 3.4) T/I C

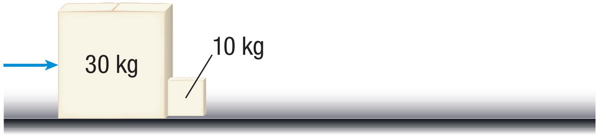


Figure 5

    (a) Calculate the acceleration of the boxes during the first 5.0 s.
    (b) If the applied force is removed, the boxes will slow down and stop. Explain why.
    (c) Calculate the total distance travelled by the boxes.

54. Four students are playing tug-of-war. The two students on the right pull with forces of magnitude 55 N and 65 N, and weigh 60 kg and 62 kg. The two students on the left pull with forces of magnitude 58 N and 70 N, and weigh 59 kg and 64 kg. What are the magnitude and direction of the acceleration of the students? (3.3) T/I

55. The box in **Figure 6** has a mass of 85 kg. $\vec{F}_a = 10$ N [up], $\vec{F}_b = 30$ N [right], $\vec{F}_c = 25$ N [right], $\vec{F}_d = 10$ N [down], and $\vec{F}_e = 22$ N [left]. (3.3) T/I

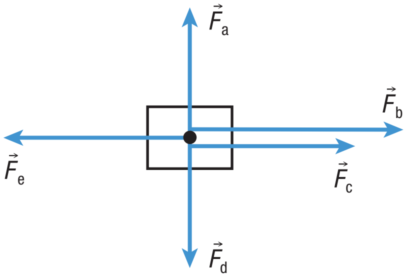


Figure 6

    (a) What is the net force acting on the box in both the vertical and horizontal directions?
    (b) What is the acceleration of the box?

56. Suppose the box in Figure 6 has a net acceleration of magnitude 5.5 m/s^2. $\vec{F}_a = 13$ N [up], $\vec{F}_b = 12$ N [right], $\vec{F}_c = 19$ N [right], $\vec{F}_d = 26$ N [down], and $\vec{F}_e = 31$ N [left]. (3.3) T/I
    (a) What is the net force acting on the box in both the vertical and horizontal directions? In which direction does the box move?
    (b) What is the mass of the box?

57. Suppose the box in Figure 6 has a mass of 12 kg. $\vec{F}_a = 220$ N [up], $\vec{F}_b = 82$ N [right], $\vec{F}_d = 220$ N [down], and $\vec{F}_e = 112$ N [left]. The magnitude of the acceleration of the box is 1.5 m/s^2. (3.3) T/I C
    (a) If the box is moving to the right, what is the magnitude of $\vec{F}_c$?
    (b) If the box is moving to the left, what is the magnitude of $\vec{F}_c$?

58. A dogsled team has four dogs that pull a person and a sled with a combined mass of 100 kg. (3.3) T/I
    (a) They start from rest and reach a speed of 45 km/h in 2.5 s. What is the average force applied by each dog?
    (b) Suppose each dog can pull with a force of magnitude 150 N. What is the frictional force acting on the sled?

59. The Moon is much smaller than Earth, so the gravitational strength of the Moon is only about one-sixth that of Earth. (3.3) T/I A
    (a) What is the acceleration due to gravity on the Moon?
    (b) How much would a 72 kg person weigh on the Moon?
    (c) If an object falls with a force of 700 N [down] on Earth, what would the force on the same object be if it fell on the Moon?

60. A girl is standing on a raft floating on the water and jumps off to the right with a force of magnitude 100 N. The mass of the girl is 55 kg, and the mass of the raft is 120 kg. (3.4) T/I C
    (a) Describe the action and reaction forces in this situation.
    (b) Determine the acceleration of both the girl and the raft.
61. A boy and a girl are standing on skateboards. The boy pushes off the girl to the left with a force of magnitude 74 N. The mass of the boy is 62 kg and the mass of the girl is 59 kg. Ignore friction. (3.4) T/I C
    (a) State the action and reaction forces in this situation.
    (b) Determine the magnitude and direction of the acceleration of each skateboarder.
62. Two ice skaters are playing a game. Skater A pushes off skater B. Skater A has a mass of 75 kg and accelerates with a magnitude of 1.2 m/s^2. Skater B accelerates with a magnitude of 0.80 m/s^2. Ignore friction. (3.4) T/I C
    (a) Based on their accelerations, which skater has more mass?
    (b) State the action and reaction forces and calculate their values.
    (c) Calculate the mass of skater B.
63. Students are performing an experiment about Newton's third law using skateboards. Student A has a mass of 58 kg and pushes off student B with a force of magnitude 80.0 N. Student B has a mass of 55 kg and has placed a block of unknown mass with him on his skateboard. (3.4) T/I C
    (a) Calculate the acceleration of student A.
    (b) If the magnitude of the acceleration of student B is greater than that of student A, what range of values could the mass of the block have? What if the magnitude of the acceleration of student B is less than that of student A?
    (c) If student B accelerates with a magnitude of 1.25 m/s^2, what is the mass of the block?
64. A male astronaut (82 kg) and a female astronaut (64 kg) are floating side by side in space. (3.4) T/I C
    (a) Determine the acceleration of each if the woman pushes on the man with a force of 16 N [left].
    (b) How will your answers change if the man pushes with 16 N [right] on the woman instead?
65. A locomotive with a mass of 6.4×10^5 kg is accelerating with a magnitude of 0.12 m/s^2 while pulling a train car of mass 5.3×10^5 kg. Assume that negligible friction is acting on the train. (3.5) T/I
    (a) Calculate the net force on the entire train.
    (b) Determine the tension between the locomotive and the train car.
66. Two objects are hung from strings (**Figure 7**). The top object (m_1) has a mass of 18 kg and the bottom object (m_2) has a mass of 12 kg. (3.5) T/I
    (a) Calculate the tension in each string.
    (b) Calculate the tension in each string if you pull down on m_1 with a force of 45 N [down].
    (c) Calculate the tension in each string if you pull down on m_2 with a force of 45 N [down].
    (d) Compare your answers to parts (b) and (c) and explain any differences.
    (e) If you keep increasing the downward force on m_2, which string will most likely break first? Explain your reasoning by assuming that both strings are identical.

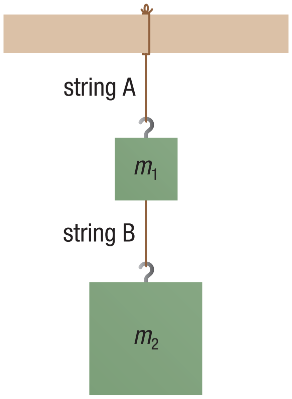


Figure 7

67. The blocks in **Figure 8** are pulled to the right and accelerate with a magnitude of 1.1 m/s^2. If $m_1 = 4.0$ kg, $m_2 = 2.3$ kg, and $m_3 = 3.4$ kg, calculate the tension in each string. Assume that friction is negligible. (3.5) T/I

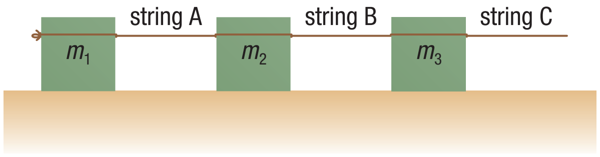


Figure 8

68. Suppose the blocks in Figure 8 are pulled to the right with a force of magnitude 15 N. If $m_1 = 4.3$ kg, $m_2 = 5.5$ kg, and $m_3 = 3.1$ kg, calculate the tension in each string and the acceleration of the blocks. Ignore friction. (3.5) T/I
69. Suppose the blocks in Figure 8 are pulled to the right with a force of magnitude 24 N. The tension in string B is twice that of the tension in string A. If $m_1 = 10$ kg and $m_3 = 8$ kg, calculate the tension in each string and the mass of m_2. Ignore friction. (3.5) T/I

70. A student has tied together two sleds with a rope. Two of his friends, with masses of 55.0 kg and 60.0 kg, are riding in the sleds, one in each (55.0 kg in the back, 60.0 kg in front). The student uses another rope to pull the sleds with a horizontal force of magnitude 230 N. The sleds accelerate with a magnitude of 1.02 m/s^2. The front sled experiences a force of friction of magnitude 58.8 N. Assume that the masses of the sleds are negligible. (3.5) T/I
    (a) What is the frictional force on the back sled?
    (b) What is the tension in the rope connecting the sleds?
    (c) The student pulling the sleds starts from rest, runs for 3.00 s, and then lets the sleds go. How far will the sleds travel after he lets them go?

Evaluation

71. The planets are constantly changing position around the Sun and have been closely following the same paths for millennia. However, the Sun has a small wobble in its position. Use Newton's first law and the concept of inertia to explain why this is so. (3.2) T/I C

72. The gravity of Earth attracts the Moon, just as it does objects near Earth. By Newton's third law, the force that attracts the Moon to Earth is the same force that attracts Earth to the Moon. (3.4) T/I A
    (a) Are objects on Earth attracted to the Moon?
    (b) Why does nothing fly off toward the Moon?

73. **Figure 9** shows a fan cart with the fan running but without the cart accelerating. (3.4) K/U

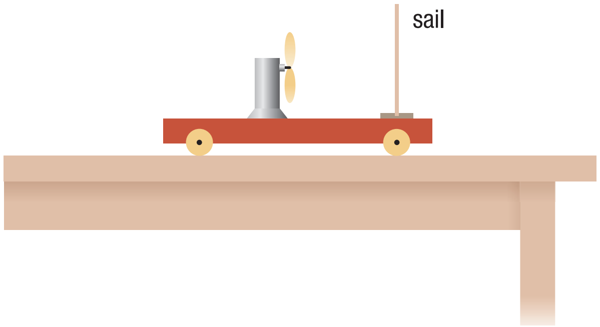


Figure 9

    (a) Explain why the fan cart cannot accelerate.
    (b) The sail is removed and the cart begins to accelerate. Explain why.

74. Two blocks are hung on opposite ends of a pulley system, as shown in **Figure 10**. The left block has a mass of 35.2 kg and the right block has a mass of 36.4 kg. (3.5) T/I

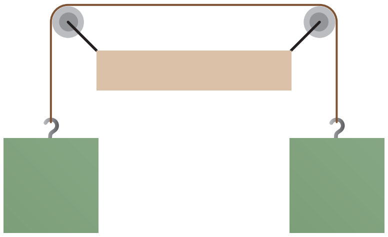


Figure 10

    (a) Is it possible for the blocks to remain stationary? What forces could be causing this to happen?
    (b) What would happen if one of the blocks were tapped downward?

Reflect on Your Learning

75. A student claims, "If action and reaction forces are equal in magnitude and opposite in direction, then when you add them together, you will always get zero and nothing will ever accelerate." Discuss the validity of this statement. C

Research

GO TO NELSON SCIENCE

76. When two positively charged particles are close together, they repel each other, and the closer the particles are, the stronger this repulsion is. However, in atoms, protons are so close together that the strong nuclear force is able to overcome the electromagnetic repulsion. Write a one-page report describing the strong nuclear force and how strong it has to be in order to hold the nucleus of atoms together. Compare this with the strength of the electromagnetic repulsion acting at the same distance. What happens in heavier elements where there are a lot of protons and thus an even stronger electromagnetic repulsion? T/I C

77. Newton is reported to have said, "If I have seen further than other men, it is because I stood on the shoulders of giants," meaning that he could not have made the discoveries that he did without the previous work of other scientists. Prepare a presentation in a format of your choice describing the knowledge of science at the time and who the primary influences were for Isaac Newton. What discoveries did they make, what observations did they make, and what experiments did they perform that helped lead Newton to his discoveries? T/I C

CHAPTER

4 Applications of Forces

KEY CONCEPTS

After completing this chapter you will be able to

- describe the relationship among mass, gravitational field strength, and the force of gravity
- analyze and solve problems involving the force of gravity and free fall
- analyze and solve problems involving friction and coefficients of friction
- conduct an inquiry that applies Newton's laws
- plan and conduct an inquiry to analyze the effects of forces acting on an object
- analyze a technology that applies Newton's laws
- evaluate the impact on society and the environment of technologies that use the principles of forces

How Do We Use Forces to Understand and Design Technology?

The Indy race car shown on the next page involves a tremendous amount of technology related to forces. The design of the powerful engine and the large wide tires is involved with increasing force. Other parts of the car that involve technology are the streamlined shape and the oil in the engine, which both help to decrease frictional forces.

One of the most prominent features of Indy cars are the wings at the front and back. These components act like inverted airplane wings, creating downward instead of upward forces on the cars. What effect, if any, does a feature like this have on the performance of the vehicle?

Another interesting design feature is the wide tires that have no treads. These tires are quite different from the all-season tires used on most vehicles in Ontario. At the start of the race, drivers drive slowly around the track together while swerving back and forth. How does this improve performance?

A great deal of technology is involved in making more powerful and efficient engines for these cars. Ideally, a driver wants a car that can move fast and accelerate quickly yet is easy to control and uses as little fuel as possible. Some of this can be accomplished by making the car, including the engine, lighter.

New innovations might one day involve coating engine parts with near-frictionless carbon. This type of coating is very easy to apply to almost any surface, and it almost eliminates friction while being very durable. However, it is very expensive and might only be used in race cars in the near future.

In this chapter, you will explore the force of gravity and frictional forces, and how these forces affect motion. You will also learn how gravity, friction, and Newton's laws can be used to design and understand different types of technology. Some of this technology, such as that used in cars, may be familiar. Other technologies, such as near-frictionless carbon and mechanical arms, may be new to you.

STARTING **POINTS**

Answer the following questions using your current knowledge. You will have a chance to revisit these questions later, applying concepts and skills from the chapter.

1. (a) Explain in your own words why the wings on the Indy car in the photograph increase the downward force on the car.
   (b) What effect, if any, does this have on the normal force acting on the car? Draw a free-body diagram (FBD) to help explain.
   (c) What effect, if any, does this have on the force of friction acting on the tires? Is this effect desirable? Explain your reasoning.
2. What effect does the surface area of the tire in contact with the road have on the magnitude of friction acting on the tire?
3. (a) Why are race car tires wider than tires on passenger cars?
   (b) Why do many car races stop when it rains?
   (c) What advantages do you think tires on passenger cars have over race car tires?
4. (a) What are some other possible applications of near-frictionless carbon?
   (b) Explain how near-frictionless carbon can help to make a car engine more efficient and last longer.

Mini Investigation

Friction from Shoes

Skills: Performing, Observing, Analyzing, Evaluating

SKILLS HANDBOOK A2.1

In this activity, you will measure the maximum force of friction that must be overcome to start moving several different types of shoes on the floor. To do this, you will use a spring scale or force sensor to measure the largest force required to move each shoe. Make sure that you know how to zero the spring scale or calibrate the force sensor.

Equipment and Materials: balance; spring scale or force sensor; four different types of shoes (dress shoes, running shoes, loafers, high-heeled shoes, etc.)

1. Examine each shoe and arrange them, from largest to smallest maximum force of friction, based on what you guess the force of friction might be.
2. Make a table with these headings: Type of shoe, Mass of shoe, F_g on shoe, Maximum force of friction, and Maximum force of friction/F_g.
3. Measure and record the mass of each shoe in your table.
4. Calculate the force of gravity on each shoe using the equation $F_g = mg$. Record the force of gravity in the table.
5. Measure the maximum force of friction for the first type of shoe. To do this, place the shoe on the floor and pull horizontally with the spring scale or the force sensor. Hook the scale or sensor to the heel of the shoe or to the laces. The maximum force of friction is equal to the largest force reading before the shoe starts moving. Record the reading in your table.
6. Repeat Step 5 for the other shoes.
7. Some shoes are heavier than others and so will be harder to start moving. To compare the shoes in a fair way, divide each maximum force of friction by the force of gravity acting on the shoe. Record your results in your table.

A. To get a fair comparison between the shoes, you divided the maximum force of friction by the force of gravity on each shoe. How does this make the comparison of the results fair? T/I

4.1 Gravitational Force Near Earth

Figure 1 A skydiver is affected by the force of gravity and air resistance.

Some people try skydiving just for the thrill. Others may skydive as part of military training. Still others like the view and the feeling of weightlessness.

The only forces acting on a skydiver jumping out of a plane are gravity and air resistance. Since the force of gravity is so much greater in magnitude than the air resistance at the beginning of the dive, the skydiver accelerates downward, initially at 9.8 m/s^2 [down]. As the skydiver continues to fall, the acceleration decreases until the skydiver reaches a constant speed (**Figure 1**). At this speed, the skydiver is no longer accelerating. In this section, you will investigate the forces that act on a falling object and why that object eventually reaches a constant speed.

Air Resistance and Free Fall

Figure 2(a) shows a small, heavy ball falling from rest. The photograph was taken using a flash that goes on and off at equal time intervals. The image of the ball was then captured at different positions during its fall. Notice that the distance between the starting position and the position in the second image is small, while the images get farther and farther apart at later times. This uneven spacing means that the ball is accelerating while it is falling.

Now look at the falling object in **Figure 2(b)**. The photograph shows a light object, a maple key, with a large cross-sectional area. The cross-sectional area is the area you see if you look directly up at the falling object. Notice that the distance between successive images in this photograph is constant. This means that the object is not accelerating but is falling with constant velocity. So the net force acting on the object in the vertical direction is zero. In this situation, another force must be acting on the falling object other than gravity. The force that balances gravity is air resistance—friction caused by the air. In this chapter, we will often ignore air resistance when examining falling objects. When an object is falling under the influence of gravity only, the object is said to be in **free fall**.

free fall the motion of a falling object where the only force acting on the object is gravity

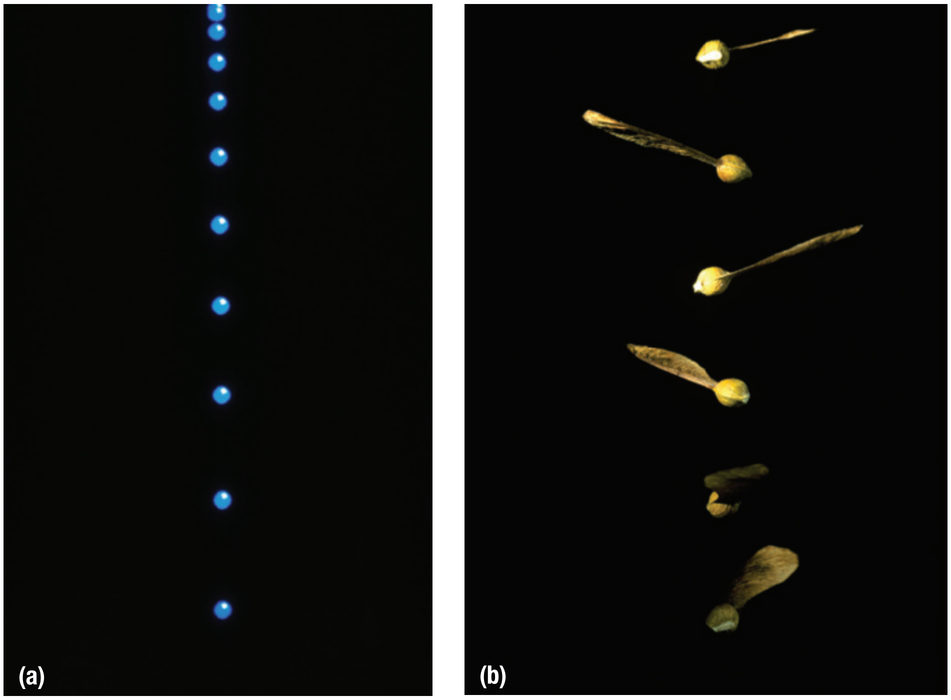


Figure 2 (a) Multi-flash photograph of a ball in free fall starting from rest (b) Multi-flash photograph of a light object with large surface area in free fall. Which object is accelerating? How can you tell?

The force of air resistance acting on an object depends on many factors. One factor is the cross-sectional area of the object. Larger cross-sectional areas experience more air resistance than smaller cross-sectional areas. To test this, hold a sheet of paper horizontally in one hand and an identical sheet of paper crumpled up into a ball in the other hand. Then drop both objects from the same height. You will notice that the crumpled paper falls much more quickly than the sheet of paper. Both objects have the same mass and experience the same force of gravity. However, the air resistance acting on each object is quite different. The horizontal sheet of paper has a larger cross-sectional area, so it experiences more air resistance. Another factor that affects the force of air resistance is the speed of the object. Faster-moving objects experience more air resistance. Air resistance acts opposite to the direction of motion of the object if there is no wind.

Now we return to the example of the skydiver. The skydiver jumps out of the plane and starts falling. The instant the skydiver leaves the plane, her initial velocity in the vertical direction is zero and she experiences very little air resistance (**Figure 3(a)**). As the skydiver continues to fall, her speed increases and she is now accelerating. As the speed of the skydiver increases, the magnitude of air resistance acting on her also increases (**Figure 3(b)**). During the time that the air resistance is increasing, the net force on the skydiver is decreasing. This means that the acceleration of the skydiver is decreasing. Eventually the magnitude of air resistance becomes great enough that it equals the magnitude of the force of gravity (**Figure 3(c)**). At this moment, the skydiver is moving at constant speed. The maximum constant speed reached by a falling object is called the **terminal speed**.

terminal speed the maximum constant speed of a falling object

To slow down, the skydiver must increase the force of air resistance acting on her body. To do this, the skydiver must increase her cross-sectional area moving through the air. So she opens her parachute. As soon as the parachute opens, the upward force of air resistance is much greater in magnitude than the downward force of gravity (**Figure 3(d)**). So the skydiver begins to slow down because the net force is directed upward while she is still falling downward. Since the speed of the skydiver is decreasing, the force of air resistance acting on the skydiver also decreases (**Figure 3(e)**). Eventually the air resistance decreases to the point where its magnitude again equals the force of gravity (**Figure 3(f)**). Now the skydiver is moving at a much slower terminal speed than before and she can land safely on the ground.

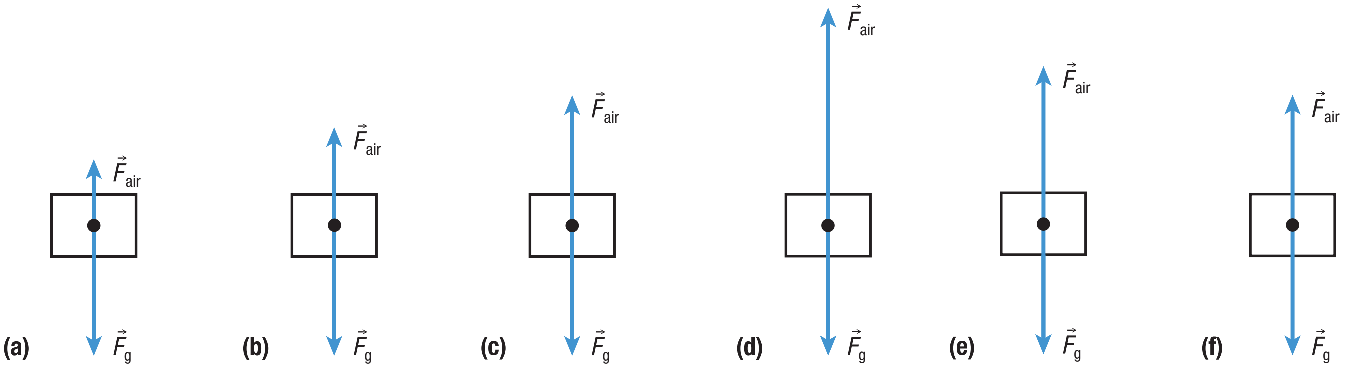


Figure 3 FBDs of a skydiver in free fall under various conditions. (a) The magnitude of air resistance is small at the beginning because the speed is small. (b) As the speed increases, so does the magnitude of air resistance. (c) Eventually the skydiver reaches a terminal speed. (d) The parachute opens and the magnitude of air resistance increases, and the skydiver slows down. (e) As the skydiver continues to slow down, the magnitude of air resistance decreases. (f) The terminal speed is lower with the parachute open.

Gravitational Field Strength

force field a region of space surrounding an object that can exert a force on other objects that are placed within that region and are able to interact with that force

How can Earth pull on objects and make them fall toward its centre? Gravity is an action-at-a-distance force that pulls on objects without making any contact with them. This occurs because Earth is surrounded by a gravitational force field. A **force field** is a region of space surrounding an object that can exert a force on other objects; the field exerts a force only on objects placed within that region that are able to interact with that force. To represent the force field around Earth, we draw lines of force that point toward Earth's centre (**Figure 4**). No matter how large or small the mass of an object is, the object will always be attracted to Earth when it interacts with this force field.

gravitational field strength the force per unit mass acting on an object when placed in a gravitational field

To determine the magnitude of Earth's gravitational force field at a particular location near its surface, physicists use a quantity called gravitational field strength. The **gravitational field strength** is the force, per kilogram of mass, acting on an object within a gravitational field. The gravitational field strength is a vector quantity because it has a direction. The gravitational field strength due to Earth always points toward Earth's centre. Gravitational field strength has units of newtons per kilogram. At Earth's surface, the gravitational field strength is 9.8 N/kg [down]. Notice that this has the same magnitude as the acceleration due to gravity at Earth's surface. In other words, the gravitational field strength at a location has the same magnitude as the acceleration due to gravity at that location. To determine the gravitational field strength at a particular location, you can measure the force of gravity acting on an object using a spring scale or force sensor and divide by the mass of the object. Then you can use the equation $\vec{F}_g = m\vec{g}$ to solve for $\vec{g}$:

$$\vec{g} = \frac{\vec{F}_g}{m}$$

Careful measurements of Earth's gravitational field strength show that its magnitude decreases as an object is moved farther away from Earth's surface. If the distance is large enough, Earth's gravitational field strength becomes very weak. For example, if the distance between an object and Earth's surface (at sea level) is equal to one Earth radius, the gravitational field strength is only 2.45 N/kg [down]. Of course, objects are not normally this far away from Earth's surface. Even at the top of Mount Everest at an altitude of 8848 m above sea level, the magnitude of the gravitational field strength is 9.7647 N/kg.

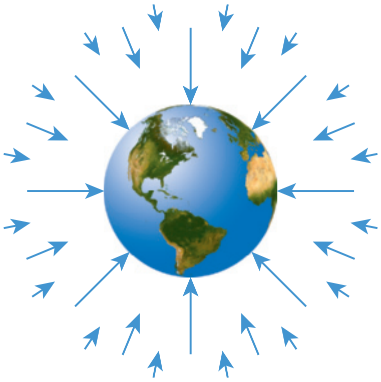


Figure 4 The gravitational force field surrounding Earth attracts all other objects placed within this field. The magnitude of Earth's gravitational field decreases as an object moves farther away from Earth's surface.

Since Earth is not a perfect sphere, the magnitude of the gravitational field strength at Earth's surface varies according to the geographic location of the object (**Figure 5**). Earth bulges out slightly at the equator due to the rotation of the planet. At the poles, an object at sea level is 21 km closer to Earth's centre than if it were at sea level at the equator. This means that the magnitude of the gravitational field strength is slightly greater at the poles than at the equator. For example, at the North Pole the magnitude of the gravitational field strength is 9.8322 N/kg, whereas at the equator it is 9.7805 N/kg. The magnitude of the gravitational field strength gradually increases with latitude as you travel from the equator toward either pole. On average, the gravitational field strength on Earth's surface is 9.8 N/kg [down], to two significant digits.

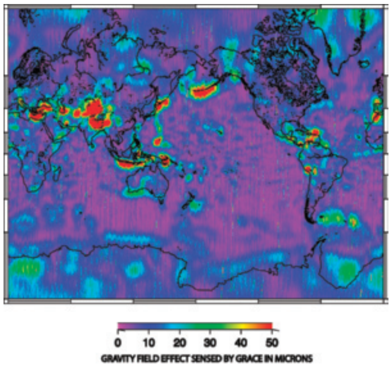


Figure 5 The magnitude of the gravitational field strength varies depending on the location on Earth's surface. On this map, red and yellow areas have a greater gravitational field strength.

The Difference between Mass and Weight

The terms "mass" and "weight" are used interchangeably in everyday language, but these two words have different meanings. Mass is the quantity of matter in an object. The only way to change the mass of an object is to either add or remove matter. The mass of an object does not change due to location or changes in gravitational field strength. The units of mass are kilograms, and mass is measured using a balance.

Weight is a measure of the force of gravity, $\vec{F}_g$, acting on an object. Since weight and the force of gravity are the same quantity, the weight of an object depends on location and the magnitude of Earth's gravitational field strength at that location. Weight is a vector, and its magnitude is measured in newtons with a spring scale or a force sensor. When measuring weight with a force sensor or a spring scale, the object must either be at rest or moving at a constant velocity while being supported by the scale or sensor.

On the Moon or a planet other than Earth, your weight is different but your mass is the same. For example, the magnitude of the gravitational field strength on the surface of the Moon is approximately one-sixth that on Earth's surface. This means that the force of gravity is weaker on the Moon and the magnitude of your weight is less. However, your body contains the same amount of matter at either location, so your mass is unchanged.

Astronauts aboard the International Space Station (ISS) appear to float within the station while they are performing tasks (**Figure 6**). This is often referred to as "weightlessness" or "microgravity." These terms are misleading because the force of gravity still acts on the astronauts—they are being pulled toward Earth's centre. In fact, gravity is the force that keeps the station and the astronauts in orbit. Without Earth's gravitational pull, the ISS would float off into space in a straight line at constant velocity. In reality, the astronauts and the ISS are in free fall.

You can experience a sensation of microgravity or apparent weight by travelling in an elevator. When the elevator is moving at a constant velocity, either up or down, everything appears normal. However, if the elevator accelerates upward, you feel heavier. If the elevator accelerates downward, you feel lighter. The following Tutorial will help to clarify how the vertical acceleration of an object such as an elevator affects how light or heavy you feel.

Figure 6 Canadian astronauts Julie Payette and Robert Thirsk on the ISS. Although these astronauts appear to be floating, they are actually in free fall.

CAREER **LINK**

To learn more about becoming an astronaut,

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Investigation **4.1.1**

Acceleration Due to Gravity and Terminal Speed (p. 191)

You will explore factors that affect the acceleration due to gravity at your location and measure its value.

Tutorial 1 The Normal Force Is Not Always Equal in Magnitude to the Force of Gravity

The following Sample Problems demonstrate the relationship between the force of gravity and the normal force.

Sample Problem 1: Cart on an Incline

A cart rolls down an incline. Assume that friction is negligible. Draw an FBD for the cart. In which directions do the normal force and the force of gravity act on the cart?

Solution

First draw the FBD of the cart (**Figure 7**). The force of gravity on the cart is down since Earth attracts all masses toward its centre. However, the normal force is perpendicular to the surface. Since the surface of the ramp is tilted, the normal force is not directly up. This example clearly shows that the normal force and the force of gravity do not always act in opposite directions.

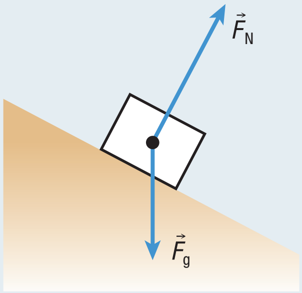


Figure 7

Sample Problem 2: Person Accelerating Up in an Elevator

A 50 kg person is standing on a bathroom scale inside an elevator. The scale is calibrated in newtons. What is the reading on the scale when the elevator is accelerating up at 2.2 m/s^2?

Solution

Step 1. Choose up as positive and down as negative.
Determine the force of gravity acting on the person.

$$\begin{aligned}\vec{F}_g &= m\vec{g}\\ F_g &= (50\text{ kg})(-9.8\text{ N/kg})\\ &= -490\text{ N}\\ F_g &= 490\text{ N [down]}\end{aligned}$$

Step 2. Now draw the FBD of the person (**Figure 8**).

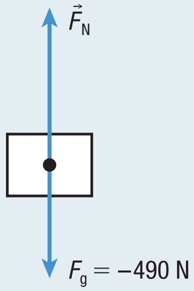


Figure 8

Step 3. Determine the normal force acting on the person. Since the elevator is accelerating up, the person is also accelerating up. The person's acceleration is equal to the elevator's acceleration.

$$\begin{aligned}\vec{F}_N + \vec{F}_g &= m\vec{a}\\ F_N + (-490\text{ N}) &= ma\\ F_N - 490\text{ N} &= (50\text{ kg})(2.2\text{ m/s}^2)\\ F_N &= 600\text{ N}\end{aligned}$$

The reading on the scale is equal to the normal force. The reading on the scale is 600 N.

Sample Problem 3: Pushing on a Person Standing on a Bathroom Scale

A 60.0 kg person is standing on a bathroom scale calibrated in newtons. A friend pushes down on the person with a force of 72.0 N. What is the reading on the scale?

Solution

Step 1. Choose up as positive and down as negative.
Determine the force of gravity acting on the person.

$$\begin{aligned}\vec{F}_g &= m\vec{g}\\ F_g &= (60\text{ kg})(-9.8\text{ N/kg})\\ &= -588\text{ N}\\ F_g &= 588\text{ N [down]}\end{aligned}$$

Step 2. Now draw the FBD of the person (**Figure 9**).

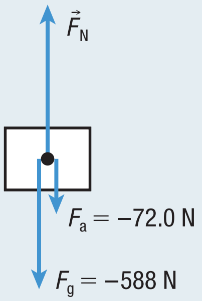


Figure 9

Step 3. Determine the normal force acting on the person. Since the person is at rest and not accelerating, the net force must be zero.

$$\begin{aligned}\vec{F}_N + \vec{F}_g + \vec{F}_a &= 0\\ F_N + (-588\text{ N}) + (-72.0\text{ N}) &= 0\\ F_N &= 660\text{ N}\end{aligned}$$

The reading on the scale is equal to the normal force. The reading on the scale is 660 N.

The last two examples show that the normal force is not always equal in magnitude to the force of gravity.

Practice

1. A 12 kg box sits on top of a 38 kg box. T/I C
   (a) Draw an FBD for each box.
   (b) Calculate the normal force acting on the 12 kg box. [ans: 120 N [up]]
   (c) Calculate the normal force acting on the 38 kg box due to the floor. [ans: 490 N [up]]
2. A child has a mass of 36 kg and is sitting on a seat on an amusement park ride. The ride makes the seat move up and down. Determine the normal force acting on the child when the child is
   (a) moving up at a constant velocity of 12 m/s [ans: 350 N [up]]
   (b) moving down at a constant velocity of 14 m/s [ans: 350 N [up]]
   (c) accelerating down at 1.8 m/s^2 T/I [ans: 290 N [up]]
3. A 72 kg person jumps up off a bathroom scale. Determine the acceleration of the person when the scale reads 840 N. T/I [ans: 1.9 m/s^2 [up]]
4. An electrician holds a 3.2 kg chandelier against a ceiling with a force of 53 N [up]. What is the normal force exerted by the ceiling on the chandelier? T/I [ans: 22 N [down]]

4.1 Summary

- Air resistance increases with the cross-sectional area and the speed of the object. Air resistance acts in a direction opposite to the velocity of the object.
- Force fields cause action-at-a-distance forces.
- The gravitational field strength is the force per unit mass acting on an object placed in a gravitational field. The gravitational field strength at Earth's surface is $\vec{g}$ = 9.8 N/kg [down]. This value decreases with distance from the surface of Earth. It is greater at the poles and less at the equator because Earth is not a perfect sphere.

4.1 Questions

1. Use Newton's second law and the force of gravity to explain why all objects fall with the same acceleration in the absence of air resistance. K/U
2. Explain why a person with an open parachute has a lower terminal speed than a person with a closed parachute. K/U
3. Why do light objects with large cross-sectional areas fall more slowly in air than heavy objects with small cross-sectional areas? K/U
4. In an action movie, a plane releases a heavy box while in flight. The box is attached to a parachute that opens as soon as it leaves the plane. Part of the way down to the ground, the parachute malfunctions and the box breaks free. Describe the forces acting on the box while it is falling and use them to describe the velocity and acceleration of the box. Use FBDs to explain your reasoning. K/U C
5. An astronaut with a mass of 74 kg goes up to the ISS on a mission. During his stay, the gravitational field strength on the station is 8.6 N/kg. T/I
   (a) What is the mass of the astronaut on the station?
   (b) What is the difference between the astronaut's weight on Earth's surface and his weight on the station?
   (c) Why does the weight of the astronaut change but not his mass when moving from the surface of Earth to the station?
   (d) Why does the astronaut appear weightless on the station?
6. Copy and complete **Table 1** by calculating the weight of an object of mass 20.000 kg at different latitudes on Earth. Use the results to answer the following questions. T/I

Table 1

Latitude (°)	Weight of object (N)	$\vec{g}$ (N/kg [down])	Distance from Earth's centre (km)
0 (equator)		9.7805	6378
30		9.7934	6373
60		9.8192	6362
90 (North Pole)		9.8322	6357

   (a) What is the difference in the weight of the object from the equator to the North Pole?
   (b) Why does the weight change at different latitudes?
   (c) Explain why the gravitational field strength increases with latitude.
7. A cargo box on a rocket has a mass of 32.00 kg. The rocket will travel from Earth to the Moon. K/U T/I
   (a) What will happen to the mass of the cargo box during the mission? Explain your reasoning.
   (b) Determine the weight of the box at the surface of Earth.
   (c) The weight of the box on the Moon is 52.06 N. Determine the gravitational field strength on the surface of the Moon.
8. Summarize the differences between mass and weight by copying and completing **Table 2**. K/U

Table 2

Quantity	Definition	Symbol	SI unit	Method of measuring	Variation with location
mass					
weight					

9. Copy **Table 3** and complete it for a 57 kg object on each planet. T/I

Table 3

Planet	Weight (N)	$\vec{g}$ (N/kg)
Mercury	188	
Venus	462	
Jupiter		26

10. A 24 kg object sits on top of a scale calibrated in newtons. Determine the reading on the scale if
   (a) the object is at rest and no one is pushing on it
   (b) the object is at rest and someone is pushing on it with a force of 52 N [down]
   (c) the object is at rest and someone is pulling on it with a force of 74 N [up] T/I

4.2 Friction

Sometimes friction is a problem and we try to minimize its effects. For example, by adding wax to skis (**Figure 1(a)**), a skier can reduce friction between the skis and the snow. The type of wax used depends on the snow temperature. In the flexible joints of the human body (**Figure 1(b)**), synovial fluid helps reduce friction between the moving bones. When there is too much friction, these joints can become very painful.

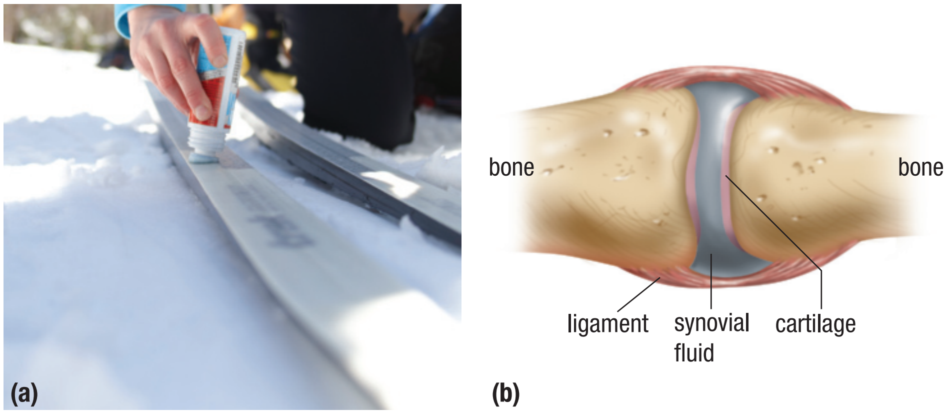


Figure 1 (a) Waxing skis helps to reduce friction. Different types of wax are used for different snow temperatures. (b) A typical flexible joint in the human body. Like oil in a car engine or wax on a ski, synovial fluid helps reduce friction between the layers of cartilage lining a flexible joint.

Other times, friction is necessary. When a car is starting to move or a person is walking or running, friction is needed. Without friction, cars could not slow down or turn corners. In this section, you will learn about the factors that affect the force of friction acting on objects and ways to control friction.

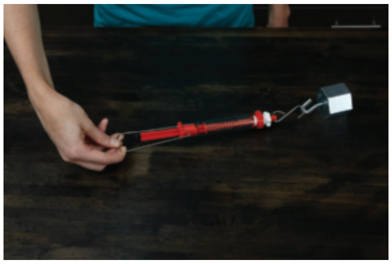


Figure 2 A force sensor is used to pull an object horizontally. Static friction keeps the object at rest.

The Difference between Static and Kinetic Friction

To help clarify the difference between static and kinetic friction, consider the following experiment. We use a force sensor to pull an object along a horizontal surface. At first the sensor exerts no force on the object, but we gradually pull with more force (**Figure 2**). Initially the object does not move due to static friction. **Static friction ($\vec{F}_S$)** is the force exerted on a stationary object by a surface that prevents the object from starting to move. In this case, the object remains at rest because the static friction is equal in magnitude and opposite in direction to the applied force.

static friction ($\vec{F}_S$) a force of friction that prevents the sliding of two surfaces relative to one another

Eventually the applied force becomes large enough to start moving the object. This means a maximum amount of static friction ($\vec{F}_{S_{max}}$) must be overcome to cause a stationary object to begin to move.

Once the object starts moving, kinetic friction, not static friction, acts on the object. **Kinetic friction ($\vec{F}_K$)** is the force exerted on a moving object by a surface, and acts opposite to the direction of motion of the object. As the applied force continues to increase, the object begins to accelerate. If the applied force decreases and the object starts moving at a constant velocity, the applied force must be equal in magnitude to the kinetic friction. **Figure 3** shows the graph of the force of friction versus the applied force during this experiment. Notice that during the time that static friction acts on the object, F_S equals F_a. So, during that time the graph is a straight line starting from the origin with a slope of 1.

kinetic friction ($\vec{F}_K$) the force exerted on a moving object by a surface opposite to the direction of motion of the object

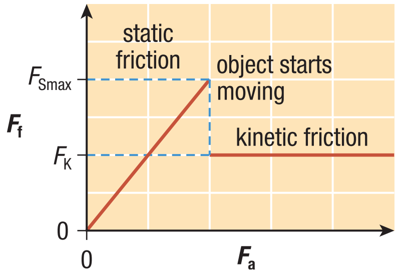


Figure 3 A graph of the magnitude of friction versus the magnitude of the applied force. Once the object starts to move, the friction drops suddenly.

Different types of kinetic friction apply to different situations. If an object is scraping or sliding across a surface, we call it sliding friction. If the object is round and it rolls across a surface, it is called rolling friction. Fluid friction or air resistance (also known as drag) are involved when a boat goes through water or a plane moves through the air. In this chapter, we will deal with sliding friction for most of the problems. However, we will use the generic term "kinetic friction" under most circumstances.

Coefficients of Friction

Many factors affect the force of friction acting on an object. The magnitude of friction acting on an object may depend on the mass of the object, the type of material the object is made of, and the type of surface the object is in contact with. When dealing with air resistance, the speed of the object and the shape of the object also have an effect. In this section, we will deal only with friction acting on an object in contact with horizontal surfaces. The only applied forces acting on the object will be horizontal.

Many experiments have been done to measure the magnitude of kinetic friction and the maximum force of static friction. Kinetic friction and static friction depend on the types of materials in the two surfaces that are in contact. However, for a particular pair of surfaces, the ratio of the frictional force (kinetic or static) to the normal force is a constant. This has led to the definition of a quantity called the coefficient of friction. The **coefficient of friction** is the ratio of the magnitude of the force of friction, F_f, acting on an object to the magnitude of the normal force, F_N, acting on the object (**Figure 4**). The Greek letter μ is used to represent the coefficient of friction. We define the coefficient of friction mathematically as

$$\mu = \frac{F_f}{F_N}$$

where F_f is the magnitude of the force of friction acting on an object in newtons, F_N is the magnitude of the normal force acting on the object in newtons, and μ is the coefficient of friction. The coefficient of friction is just a number, with no direction or units.

To calculate the coefficient of static friction for an object on a surface, we need to determine the maximum force of static friction in that particular situation. For almost all situations, the force required to start an object moving is greater than the kinetic resistance acting on the object when it is moving. This means that $F_{S_{max}}$ is usually slightly greater than F_K. Since there are two types of friction (static and kinetic), there are two coefficients of friction. One is the **coefficient of static friction**, which represents the ratio of $F_{S_{max}}$ to the normal force. The coefficient of static friction is represented by the symbol μ_S. The other is the **coefficient of kinetic friction**, which represents the ratio of F_K to the normal force. The coefficient of kinetic friction is represented by the symbol μ_K. Since the maximum force of static friction is usually greater than the kinetic friction, the coefficient of static friction is usually greater than the coefficient of kinetic friction. The corresponding equations are

$$\mu_S = \frac{F_{S_{max}}}{F_N} \quad \text{and} \quad \mu_K = \frac{F_K}{F_N}$$

The coefficient of friction between an object and a surface depends only on the type of materials. These coefficients of friction can only be determined experimentally. The results of such experiments are often inconsistent, even when performed carefully. Results can be affected by the condition of the surface, including the cleanliness of the surface, whether the surface is wet or dry, and the roughness of the surface. This means one scientist may obtain a different coefficient of friction than another scientist even when neither one has made any mistakes. So, in many cases, a range of values is given for coefficients of friction. **Table 1** on the next page gives several coefficients of kinetic and static friction for some common materials.

coefficient of friction (μ) the ratio of the force of friction to the normal force

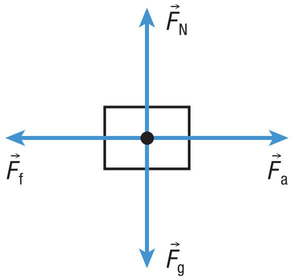


Figure 4 An FBD of an object pulled by a horizontal force. The magnitudes of the force of friction and the normal force are used to find the coefficient of friction.

coefficient of static friction (μ_S) the ratio of the maximum force of static friction to the normal force

coefficient of kinetic friction (μ_K) the ratio of kinetic friction to the normal force

Investigation **4.2.1**

Factors That Affect Friction (p. 192)
In this investigation, you will explore some of the factors that affect $F_{S_{max}}$ and F_K acting on an object. You will design your own procedure and take an average of several measurements before forming a conclusion about a specific factor.

Table 1 Approximate Coefficients of Kinetic and Static Friction

Material	μ_S	μ_K
rubber on concrete (dry)		0.6–0.85
rubber on concrete (wet)		0.45–0.75
rubber on asphalt (dry)		0.5–0.80
rubber on asphalt (wet)		0.25–0.75
steel on steel (dry)	0.78	0.42
steel on steel (greasy)	0.05–0.11	0.029–0.12
leather on oak	0.61	0.52
ice on ice	0.1	0.03
steel on ice	0.1	0.01
rubber on ice		0.005
wood on dry snow	0.22	0.18
wood on wet snow	0.14	0.10
Teflon on Teflon	0.04	0.04
near-frictionless carbon		0.001
synovial joints in humans	0.01	0.003

Investigation **4.2.2**

Coefficients of Friction (p. 193)
In this investigation, you will explore how the coefficient of static friction compares to the coefficient of kinetic friction. You will also determine some of the factors that affect these values.

In the following Tutorial, we will apply the equations for the coefficient of friction to determine the force of friction acting on a wooden block.

Tutorial **1** Determining the Forces of Friction

The following Sample Problem will help to clarify how the normal force and the force of friction are related to the coefficients of friction.

Sample Problem 1

A 3.0 kg block of wood sits on a horizontal wooden floor. The largest horizontal force that can be applied to the block before it will start moving is 14.7 N. Once the block starts moving, it only takes 8.8 N to keep it moving at a constant velocity.

(a) Calculate the coefficient of static friction for the block and the floor.

(b) Determine the force of friction acting on the block if a horizontal force of 6.8 N [E] acts on the block.

(c) Calculate the maximum magnitude of static friction acting on the block if a 2.1 kg object is placed on top of it.

(d) Determine the coefficient of kinetic friction.

Solution

(a) **Given:** $m = 3.0$ kg; $F_a = 14.7$ N

Required: μ_S

Analysis: Since the block is not moving, the net force on the block is zero. This means that $\vec{F}_{S_{max}}$ on the block must also be 14.7 N acting in the opposite direction to keep the block at rest. To calculate the coefficient of static friction, we can use the equation $\mu_S = \frac{F_{S_{max}}}{F_N}$. Also, the force of gravity must be equal to the normal force.

Solution: $\mu_S = \frac{F_{S_{max}}}{F_N} = \frac{F_{S_{max}}}{mg}$

$$= \frac{14.7 \text{ N}}{(3.0 \text{ kg})(9.8 \text{ m/s}^2)}$$

$$\mu_S = 0.50$$

Notice that $1 \text{ kg}\cdot\text{m/s}^2 = 1 \text{ N}$, so the units cancel.

Statement: The coefficient of static friction is 0.50.

(b) The horizontal applied force (6.8 N [E]) is less than the maximum force of static friction (14.7 N), so the block will remain at rest. This means the net force on the block is still zero and the applied force must be cancelled by the static friction. The static friction on the block must be 6.8 N [W].

(c) **Given:** $m_T = 3.0 \text{ kg} + 2.1 \text{ kg} = 5.1 \text{ kg}$

Required: $F_{S_{max}}$

Analysis: Since the same materials are still in contact, $\mu_S = 0.50$. To calculate the maximum force of static friction, we can use the equation $\mu_S = \frac{F_{S_{max}}}{F_N}$. Since the total mass is now 5.1 kg, we can calculate the normal force using the equation $F_N = m_T g$.

Solution: $\mu_S = \frac{F_{S_{max}}}{F_N}$

$$F_{S_{max}} = \mu_S F_N = \mu_S m_T g$$

$$= (0.50)(5.1 \text{ kg})(9.8 \text{ m/s}^2)$$

$$F_{S_{max}} = 25 \text{ N}$$

Statement: The maximum magnitude of static friction acting on the block is 25 N.

(d) **Given:** $m = 3.0 \text{ kg}$; $F_a = 8.8 \text{ N}$

Required: μ_K

Analysis: The block is moving with a constant velocity, so the net force on the block is zero. This means the kinetic friction, F_K, on the block must also be 8.8 N acting in the opposite direction. To find the coefficient of kinetic friction we can use the equation $\mu_K = \frac{F_K}{F_N}$.

Solution:

$$\mu_K = \frac{F_K}{F_N} = \frac{F_K}{mg}$$

$$= \frac{8.8 \text{ N}}{(3.0 \text{ kg})(9.8 \text{ m/s}^2)}$$

$$\mu_K = 0.30$$

Statement: The coefficient of kinetic friction is 0.30.

Practice

1. Determine the coefficient of friction for each situation. T/I
   (a) It takes a horizontal force of 62 N to get a 22 kg box to just start moving across the floor. [ans: 0.29]
   (b) It only takes 58 N of horizontal force to move the same box at a constant velocity. [ans: 0.27]
2. A 75 kg hockey player glides across the ice on his skates with steel blades. What is the magnitude of the force of friction acting on the skater? Use **Table 1** to help you. T/I [ans: 7.4 N]
3. A 1300 kg car skids across an asphalt road. Use **Table 1** to calculate the magnitude of the force of friction acting on the car due to the road if the road is
   (a) dry [ans: 6000 N to 10 000 N]
   (b) wet [ans: 3200 N to 9600 N]
   (c) covered with ice T/I [ans: 64 N]

4.2 Summary

- Static friction ($\vec{F}_S$) is the force of friction that prevents two surfaces in contact from sliding relative to one another.
- The maximum force of static friction ($\vec{F}_{S_{max}}$) is the amount of force that must be overcome to start a stationary object moving.
- Kinetic friction ($\vec{F}_K$) is the force exerted on a moving object by a surface. Kinetic friction acts in the opposite direction to the motion of the object.
- The coefficient of friction is the ratio of the force of static or kinetic friction to the normal force. The equations are $\mu_S = \frac{F_{S_{max}}}{F_N}$ and $\mu_K = \frac{F_K}{F_N}$.
- Coefficients of friction are determined experimentally and depend only on the types of materials in contact.

4.2 Questions

1. For each situation, determine if friction is helpful, makes the action more difficult, or both. Explain your reasoning. K/U
   - (a) turning a doorknob
   - (b) pushing a heavy box across a rough surface
   - (c) gliding across smooth ice to demonstrate uniform motion
   - (d) tying a knot
2. A typical bicycle braking system involves a lever that you pull on the handlebars and a brake pad near the rim of the wheel **(Figure 5)**. Describe how the braking system works using the concepts of normal force and friction. K/U C

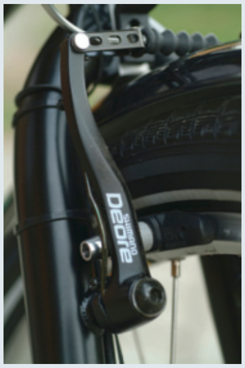


Figure 5

3. A 1.4 kg block on a horizontal surface is pulled by a horizontal applied force. It takes 5.5 N to start the block moving and 4.1 N to keep it moving at a constant velocity. T/I
   - (a) Calculate the coefficients of friction.
   - (b) Which changes below will affect the coefficients of friction? Explain.
     - (i) turning the block onto another side
     - (ii) changing the surface
     - (iii) putting an object on top of the block
   - (c) What effect will each situation have on the static and kinetic friction acting on each object? Explain.
     - (i) putting an object on the block
     - (ii) applying an upward force on the block
     - (iii) putting slippery grease on the surface
4. Examine the coefficients of friction in **Table 1** on page 170 to answer the following. A
   - (a) Roads in Canada are typically made out of asphalt or concrete. Is one material significantly safer than the other? Explain your reasoning.
   - (b) Explain why drivers should reduce speed on wet roads.
   - (c) Why do we salt roads in the winter, especially when there is freezing rain?
5. You are dragging a 110 kg trunk across a floor at a constant velocity with a horizontal force of 380 N. T/I
   - (a) Calculate the coefficient of kinetic friction.
   - (b) A friend decides to help by pulling on the trunk with a force of 150 N [up]. Will this help? Calculate the force required to pull the trunk at a constant velocity to help you decide.
   - (c) Instead of pulling on the trunk, your 55 kg friend just sits on it. What force is required keep the trunk moving at a constant velocity?
6. A 26 kg desk is at rest on the floor. The coefficient of static friction is 0.25. One person pulls on the desk with a force of 52 N [E] and another pulls with a force of 110 N [W]. Will the desk move? Explain your reasoning. T/I
7. A 12 000 kg bin is sitting in a parking lot. The coefficient of static friction for the bin is 0.50 and the coefficient of kinetic friction is 0.40. A truck pushes on the bin and it starts to move. Determine the minimum force exerted by the truck to
   - (a) start the bin moving
   - (b) keep the bin moving at a constant velocity T/I
8. A gradually increasing horizontal force is applied to an object initially at rest on a horizontal surface. Draw a graph of the force of friction versus the applied force in each situation. T/I C
   - (a) the coefficient of static friction is slightly greater than the coefficient of kinetic friction
   - (b) the coefficient of static friction is equal to the coefficient of kinetic friction
9. A doorstop keeps a door open when it is wedged underneath the door. Use the concepts from this section to explain how a doorstop works. C A
10. Describe how to determine each quantity experimentally. T/I C
    - (a) the coefficient of static friction
    - (b) the coefficient of kinetic friction
11. Explain why the manufacturer of a running shoe might be more concerned about having a high coefficient of friction than the manufacturer of a dress shoe. C A

Solving Friction Problems

Sometimes friction is desirable and we want to increase the coefficient of friction to help keep objects at rest. For example, a running shoe is typically designed to have a large coefficient of friction between the sole and the floor or ground (**Figure 1**). The design of the sole involves choosing materials with high coefficients of friction, and shaping the sole to increase friction under wet conditions, among other factors. Even the appearance is important because people want their shoes to look good.

However, sometimes we want as little friction as possible. A hockey player shooting a puck toward the net does not want the puck to slow down as it moves across the ice (**Figure 2**). In transportation technologies, you want to minimize the force of friction acting on accelerating railway cars and trailers pulled by trucks. In this section, you will explore how the force of friction affects the motion of an object, whether the object is at rest or in motion. You will also learn how to solve problems involving friction.

Static Friction Problems

Sometimes when you push on an object, it does not move. The reason is that static friction is acting on the object. If two or more objects are attached, you must overcome the combined maximum force of static friction to cause the objects to move. For example, when a train pulls several railway cars forward, it must exert enough force to overcome the combined maximum force of static friction acting on all the railway cars. If the applied force acting on the railway cars is less than this combined force of static friction, the cars will not move. In the following Tutorial, we will examine the effect of static friction when it is acting on more than one object.

Figure 1 The sole of a running shoe is designed to increase friction to help runners accelerate quickly.

Figure 2 When a puck moves across the ice, it is better to have less friction.

Tutorial 1 Static Friction Acting on Several Objects

In the following Sample Problem, we will use the coefficient of friction to determine the forces acting on sleds being pulled by an adult.

Sample Problem 1

Two sleds are tied together with a rope (**Figure 3**). The coefficient of static friction between each sled and the snow is 0.22. A small child is sitting on sled 1 (total mass of 27 kg) and a larger child sits on sled 2 (total mass of 38 kg). An adult pulls on the sleds.

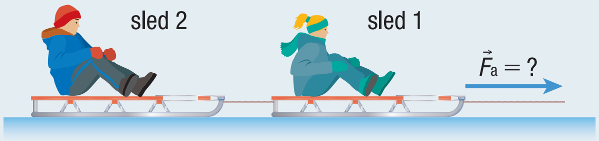


Figure 3

(a) What is the greatest horizontal force that the adult can exert on sled 1 without moving either sled?

(b) Calculate the magnitude of the tension in the rope between sleds 1 and 2 when the adult exerts this greatest horizontal force.

Solution

(a) The two sleds do not move when the adult pulls on sled 1. This means that the net force acting on the sleds is zero and the applied force must be cancelled by the total maximum force of static friction acting on the two sleds. To calculate the static friction, we combine the two masses and treat the sleds as one single object.

Given: $m_T = 27\text{ kg} + 38\text{ kg} = 65\text{ kg}$; $\mu_S = 0.22$

Required: $\vec{F}_{S_{max}}$

Analysis: $\mu_S = \dfrac{F_{S_{max}}}{F_N}$

Solution:

$$\begin{aligned} F_{S_{max}} &= \mu_S F_N \\ &= \mu_S m_T g \\ &= (0.22)(65\text{ kg})(9.8\text{ m/s}^2) \\ F_{S_{max}} &= 140\text{ N} \end{aligned}$$

Statement: The greatest horizontal force that the adult can exert on sled 1 without moving either sled is 140 N [forward].

(b) Draw the FBD for sled 2 (**Figure 4**).

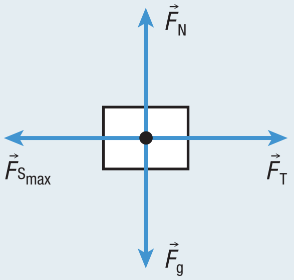


Figure 4

Keep in mind that sled 2 does not move, which means the net force is zero. In this case, the tension and the static friction acting on sled 2 will cancel.

Given: $m = 38$ kg; $\mu_S = 0.22$

Required: F_T

Analysis: Since $F_T = F_{S_{max}}$, calculate $F_{S_{max}}$ using $\mu_S = \dfrac{F_{S_{max}}}{F_N}$

Solution:

$$\begin{aligned} F_{S_{max}} &= \mu_S F_N \\ &= \mu_S mg \\ &= (0.22)(38\text{ kg})(9.8\text{ m/s}^2) \\ F_{S_{max}} &= 82\text{ N} \end{aligned}$$

Statement: The magnitude of the tension in the rope is 82 N.

Practice

1. Two trunks sit side by side on the floor. The larger trunk (52 kg) is to the left of the smaller trunk (34 kg). A person pushes on the larger trunk horizontally toward the right. The coefficient of static friction between the trunks and the floor is 0.35. T/I
   (a) Determine the magnitude of the maximum force the person can exert without moving either trunk. [ans: 290 N]
   (b) Calculate the force the larger trunk exerts on the smaller trunk. [ans: 120 N [right]]
   (c) Would either answer change if the person pushed in the opposite direction on the smaller trunk? Explain your reasoning.
2. A 4.0 kg block of wood sits on a table (**Figure 5**). A string is tied to the wood, running over a pulley and down to a hanging object. The greatest mass that can be hung from the string without moving the block of wood is 1.8 kg. Calculate the coefficient of static friction between the block of wood and the table. T/I [ans: 0.45]

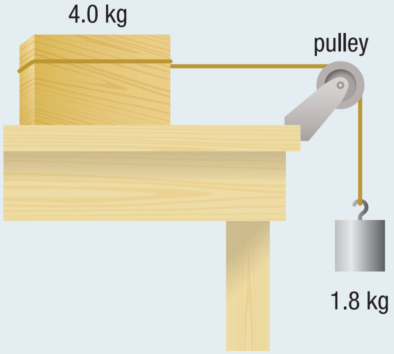


Figure 5

Figure 6 When starting a race, an athlete can achieve a greater forward acceleration by pushing backwards on starting blocks.

Static Friction and Motion

It is important to understand that static friction acts on an object when the object is at rest on a surface. This does not mean that static friction cannot be used to make an object move. For example, when you take a step forward, the bottom of your shoe is at rest with respect to the ground. The foot you are standing on is not actually moving forward with the rest of your body. The action force is you pushing backwards on the ground. According to Newton's third law, the ground pushes back on your foot with a force of equal magnitude but opposite in direction (the reaction force). This reaction force is the force of static friction, and it is this force that actually pushes you forward. Keep in mind that the force of static friction is usually greater in magnitude than the force of kinetic friction. This means that in a race from a standing start without starting blocks (**Figure 6**), you ideally want to push backwards with both feet, making sure your shoes do not slip. In the following Tutorial, we will examine the effect of static friction that causes an object to move.

Tutorial 2 Static Friction Can Cause Motion

The following Sample Problem will demonstrate how to calculate the maximum magnitude of acceleration when the coefficient of static friction is given.

Sample Problem 1

The coefficient of static friction between a person's shoe and the ground is 0.70. Determine the maximum magnitude of acceleration of the 62 kg person, if he starts running on a horizontal surface from rest.

Given: $\mu_S = 0.70$; $m = 62$ kg

Required: a

Analysis: Draw the FBD of the person (**Figure 7**).

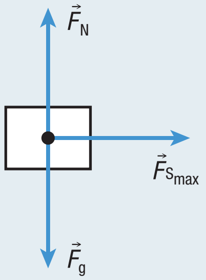


Figure 7

In this case, the maximum force of static friction is the net force since the normal force and gravity cancel. First we need to calculate $F_{S_{max}}$.

$F_{net} = F_{S_{max}}$; $F_{S_{max}} = \mu_S F_N$

Solution:
$$\begin{aligned} F_{S_{max}} &= \mu_S F_N \\ &= \mu_S mg \\ &= (0.70)(62\ \text{kg})(9.8\ \text{m/s}^2) \\ F_{S_{max}} &= 425.3\ \text{N (two extra digits carried)} \end{aligned}$$

Now calculate the magnitude of the acceleration:

$$\begin{aligned} F_{net} &= F_{S_{max}} \\ ma &= 425.3\text{N} \\ (62\ \text{kg})a &= 425.3\ \text{N} \\ a &= 6.9\ \text{m/s}^2 \end{aligned}$$

Statement: The maximum magnitude of the acceleration is 6.9 m/s^2.

Practice

1. Two people start running from rest. The first person has a mass of 59 kg and is wearing dress shoes with a coefficient of static friction of 0.52. The other person is wearing running shoes with a coefficient of static friction of 0.66. T/I
   (a) Calculate the maximum possible initial acceleration of the person wearing dress shoes. [ans: 5.1 m/s^2 [forward]]
   (b) Explain why we do not really need the mass of either person when finding the initial maximum possible acceleration.
   (c) Determine the ratio of the two accelerations and compare it to the ratio of the two coefficients of friction. [ans: 0.79; they are equal]
2. A skater with mass 58 kg is holding one end of a rope and standing at rest on ice. Assume no friction. Another person with mass 78 kg is standing just off the ice on level ground and is holding the other end of the rope. The person standing on the ground pulls on the rope to accelerate the skater forward. The coefficient of static friction between the ground and the off-ice person is 0.65. Calculate the maximum possible acceleration of the skater. T/I [ans: 8.6 m/s^2 [toward off-ice person]]

Kinetic Friction Problems

When an object is sliding across a surface, kinetic friction acts on the object in a direction opposite to the direction of motion. One common misconception is that kinetic friction always reduces the net force acting on an object. For example, in Sample Problem 1 in Tutorial 3, a person pushes against a sliding box to stop it from sliding any farther. In this situation, both the applied force and the kinetic friction act in the same direction (**Figure 8(a)**). So the magnitude of the net force is greater than if the person applies a force in the opposite direction (**Figure 8(b)**). In the following Tutorial, we will examine how kinetic friction causes a moving object to come to rest.

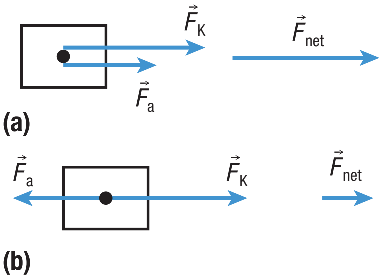


Figure 8 (a) Both the applied force and friction act in the same direction, producing a large net force. (b) The applied force and kinetic friction act in opposite directions, producing a smaller net force.

Tutorial 3 Kinetic Friction and Motion

The following Sample Problems will help to clarify the effect of kinetic friction on motion.

Sample Problem 1: Stopping a Sliding Box

A 250 kg box slides down a ramp and then across a level floor. The coefficient of kinetic friction along the floor is 0.20. A person sees the box moving at 1.0 m/s [left] and pushes on it with a horizontal force of 140 N [right].

(a) How far does the box travel before coming to rest?

(b) How will the results change if the box is moving right and the person still pushes right with the same force?

Solution

(a) **Given:** $\mu_K = 0.20$; $m = 250$ kg; $\vec{F}_a = 140\text{ N}\ [\text{right}]$

Required: Δd

Analysis: Draw the FBD of the box (**Figure 9**). Choose right and up as positive and left and down as negative. The kinetic friction must be opposite to the motion. We will first determine the kinetic friction. We can then use the FBD to find the acceleration. Once we have the acceleration, we can use one of the kinematics equations to calculate the distance.

$v_2^2 = v_1^2 + 2a\Delta d$; $F_K = \mu_K F_N$; $\vec{F}_{net} = \vec{F}_a + \vec{F}_K$

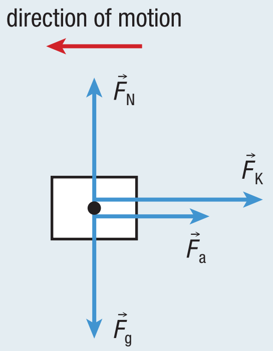


Figure 9

Solution:
$$\begin{aligned} F_K &= \mu_K F_N \\ &= \mu_K mg \\ &= (0.20)(250\text{ kg})(9.8\text{ m/s}^2) \\ &= 490\text{ N} \end{aligned}$$

Now calculate the acceleration.

$$\begin{aligned} \vec{F}_{net} &= \vec{F}_a + \vec{F}_K \\ ma &= 140\text{ N} + 490\text{ N} \\ (250\text{ kg})a &= 630\text{ N} \\ a &= 2.52\text{ m/s}^2 \\ \vec{a} &= 2.52\text{ m/s}^2\ [\text{right}]\ \text{(one extra digit carried)} \end{aligned}$$

Next calculate the distance travelled. Since we do not know the time, we use the kinematics equation $v_2^2 = v_1^2 + 2a\Delta d$.

$$\begin{aligned} v_2^2 &= v_1^2 + 2a\Delta d \\ v_2^2 - v_1^2 &= 2a\Delta d \\ \Delta d &= \frac{v_2^2 - v_1^2}{2a} \\ \Delta d &= \frac{0^2 - (-1.0\text{ m/s})^2}{2(2.52\text{ m/s}^2)} \\ \Delta d &= -0.20\text{ m} \end{aligned}$$

Statement: The box moves 0.20 m before coming to rest.

(b) In this situation, friction is directed toward the left. Since the applied force acts in the opposite direction, the net force will be smaller. So the acceleration will now also be smaller, and the box will travel farther before coming to rest.

Sample Problem 2

Two sleds tied together are pulled across an icy surface with an applied force of 150 N [E] (**Figure 10**). The mass of sled 1 is 18.0 kg and the mass of sled 2 is 12.0 kg. The coefficient of kinetic friction for each sled is 0.20.

(a) Calculate the acceleration of the sleds.

(b) Determine the magnitude of the tension in the rope between the sleds.

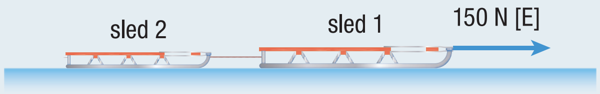


Figure 10

Solution

(a) Both sleds move together with the same acceleration so we can treat them as one large object. The total mass of the two sleds is $m_T = 18.0\text{ kg} + 12.0\text{ kg} = 30.0\text{ kg}$.

There is no need to consider the tension at this point because it is an internal force and does not contribute to the acceleration of the total mass.

Draw the FBD of the two sleds (**Figure 11**). Choose east and up as positive and west and down as negative.

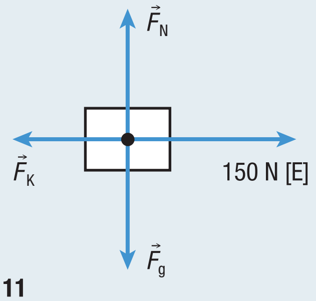


Figure 11

Given: $\mu_K = 0.20$; $m_T = 30.0$ kg; $\vec{F}_a = 150\text{ N}\ [\text{E}]$

Required: $\vec{a}$

Analysis: $\vec{F}_{\text{net}} = m\vec{a}$; $\vec{F}_{\text{net}} = \vec{F}_{\text{a}} + \vec{F}_{\text{K}}$

Solution: First we need to determine the force of kinetic friction.

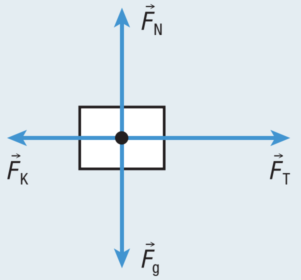
$$\begin{aligned} F_{\text{K}} &= \mu_{\text{K}} F_{\text{N}} \\ &= \mu_{\text{K}} m_{\text{T}} g \\ &= (0.20)(30.0\ \text{kg})(9.8\ \text{m/s}^2) \\ F_{\text{K}} &= 58.8\ \text{N (one extra digit carried)} \end{aligned}$$

Now calculate the acceleration.

$$\begin{aligned} \vec{F}_{\text{net}} &= \vec{F}_{\text{a}} + \vec{F}_{\text{K}} \\ m_{\text{T}} a &= 150\ \text{N} - 58.8\ \text{N} \\ (30.0\ \text{kg})a &= 91.2\ \text{N} \\ a &= 3.04\ \text{m/s}^2 \\ \vec{a} &= 3.0\ \text{m/s}^2\ [\text{E}] \end{aligned}$$

Statement: The acceleration of both sleds is 3.0 m/s^2 [E].

(b) To calculate the magnitude of the tension, we can use the FBD for sled 2.



$$\begin{aligned} \vec{F}_{\text{net}} &= \vec{F}_{\text{T}} + \vec{F}_{\text{K}_2} \\ m_2 a &= F_{\text{T}} - \mu_{\text{K}} m_2 g \\ (12.0\ \text{kg})(3.04\ \text{m/s}^2) &= F_{\text{T}} - (0.20)(12.0\ \text{kg})(9.8\ \text{m/s}^2) \\ F_{\text{T}} &= 60\ \text{N} \end{aligned}$$

Statement: The magnitude of the tension in the rope is 60 N.

Practice

1. A 0.170 kg hockey puck is initially moving at 21.2 m/s [W] along the ice. The coefficient of kinetic friction for the puck and the ice is 0.005. T/I
   (a) What is the speed of the puck after travelling 58.5 m? [ans: 21.1 m/s]
   (b) After being played on for a while, the ice becomes rougher and the coefficient of kinetic friction increases to 0.047. How far will the puck travel if its initial and final speeds are the same as before? [ans: 6.24 m]
2. A snowmobile is used to pull two sleds across the ice. The mass of the snowmobile and the rider is 320 kg. The mass of the first sled behind the snowmobile is 120 kg and the mass of the second sled is 140 kg. The ground exerts a force of 1500 N [forward] on the snowmobile. The coefficient of kinetic friction for the sleds on ice is 0.15. Assume that no other frictional forces act on the snowmobile. Calculate the acceleration of the snowmobile and sleds. T/I C [ans: 1.9 m/s^2 [forward]]
3. A string is tied to a 3.2 kg object on a table and a 1.5 kg object hanging over a pulley (**Figure 12**). The coefficient of kinetic friction between the 3.2 kg object and the table is 0.30. T/I
   (a) Calculate the acceleration of each object. [ans: 1.1 m/s^2 [R]; 1.1 m/s^2 [down]]
   (b) Determine the magnitude of the tension in the string. [ans: 13 N]
   (c) How far will the objects move in 1.2 s if the initial velocity of the 3.2 kg object is 1.3 m/s [right]? [ans: 2.4 m]
4. An electric motor is used to pull a 125 kg box across a floor using a long cable. The tension in the cable is 350 N and the box accelerates at 1.2 m/s^2 [forward] for 5.0 s. The cable breaks and the box slows down and stops. T/I C
   (a) Calculate the coefficient of kinetic friction. [ans: 0.16]
   (b) How far does the box travel up to the moment the cable breaks? [ans: 15 m]
   (c) How far does the box travel from the moment the cable breaks until it stops? [ans: 11 m]

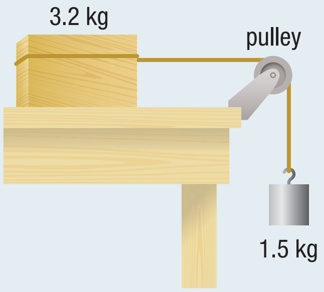


Figure 12

4.3 Summary

- Static friction exists between an object and a surface when the object is not sliding on the surface.
- Static friction can be used to move objects.
- Kinetic friction always acts in a direction that is opposite to the motion of the object.
- The kinematics equations from Unit 1 can be used to solve some problems involving friction and other forces.

Investigation 4.3.1

Predicting Motion with Friction (p. 194)

In this investigation, you will calculate the acceleration of a system of objects using Newton's laws. Then you will measure the actual acceleration.

4.3 Questions

1. During fundraising week at school, students decide to hold a competition of strength. Contestants pay $1 to try to move a heavy object. If they can move the object, they win $10. The object is a large box of books of mass 250 kg, with a coefficient of static friction of 0.55. One student has a mass of 64 kg and a coefficient of friction of static friction of 0.72 for his shoes on the floor. T/I
   (a) What is the maximum force of static friction acting on the student?
   (b) What is the maximum force of static friction acting on the box?
   (c) Is the competition fair? Explain your reasoning.
2. In an action movie, an actor is lying on an ice shelf and holding onto a rope. The rope hangs over a cliff to another actor who is hanging on in midair. The actor on the ice shelf has a mass of 55 kg and the actor hanging in midair has a mass of 78 kg. Neither actor can grab onto anything to help stop their motion, yet in the movie neither one is moving. T/I A
   (a) Calculate the minimum coefficient of static friction.
   (b) Is your answer to (a) reasonable considering that the surface is ice? Explain.
   (c) What could the director do to make the scene more realistic? Explain your reasoning.
3. In a physics experiment on static friction, two objects made of identical material are tied together with string. The first object has a mass of 5.0 kg and the second object has a mass of 3.0 kg. Students measure the maximum force of static friction as 31.4 N to move both objects across a horizontal surface. T/I
   (a) What is the coefficient of static friction?
   (b) What is the magnitude of the tension in the string if they pull on the first object?
   (c) A student pushes the 3.0 kg object with a force of 15.0 [down]. What are the magnitudes of the maximum force of static friction and the tension now?
   (d) Will your answers to (c) change if the student pushes down on the 5.0 kg object instead? Explain.
4. A student puts a 0.80 kg book against a vertical wall and pushes on the book toward the wall with a force of 26 N [R]. The book does not move. T/I
   (a) Calculate the minimum coefficient of static friction.
   (b) Describe two ways the student could make the book accelerate down without changing the applied force.
5. A string is tied to a 4.4 kg block and a 120 g hanging bucket (**Figure 13**). Students add 20 g washers one at a time to the bucket. The students are unaware that the coefficient of static friction for the block on the table is 0.42. T/I
   (a) What is the maximum force of static friction for the block?
   (b) How many washers can the students add to the bucket without moving the block?
   (c) Will this investigation yield an accurate result if they use it to find the coefficient of static friction? Explain your reasoning.
   (d) The coefficient of kinetic friction is 0.34. Calculate the acceleration of the block when the final washer is placed in the bucket and the objects start to move.

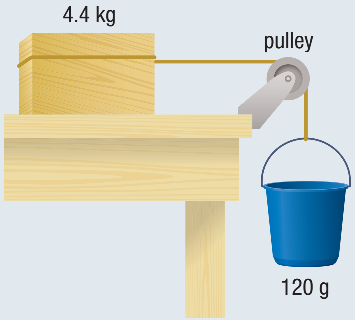


Figure 13

6. In a tug-of-war contest on a firm, horizontal sandy beach, team A has six players with an average mass of 65 kg and team B has five players with an average mass of 84 kg. Team B, pulling with a force of 3.2 kN, dislodges team A and then decreases its force to 2.9 kN to pull team A across the sand at a constant velocity. Determine team A's coefficient of
   (a) static friction (b) kinetic friction T/I
7. Two students push a 260 kg piano across the floor. Kathy pushes with 280 N [forward] while Matt pushes with 340 N [forward]. The piano accelerates at 0.30 m/s^2 [forward]. T/I
   (a) What is the coefficient of kinetic friction?
   (b) How long will it take the piano to stop moving after pushing it for 6.2 s from rest?
8. A 65 kg sprinter accelerates from rest into a strong wind that exerts a frictional force of 62 N. The ground applies a constant forward force of 250 N on the sprinter's feet. T/I
   (a) Calculate
      (i) the sprinter's acceleration
      (ii) the distance travelled in the first 2.0 s
      (iii) the minimum coefficient of friction between the sprinter's shoes and the track
   (b) Is the friction applied on the sprinter from the ground static or kinetic? Explain.
9. A homeowner accelerates a 15.0 kg lawnmower uniformly from rest to 1.2 m/s in 2.0 s. The coefficient of kinetic friction is 0.25. Calculate the horizontal applied force acting on the lawnmower. T/I
10. A 75 kg baseball player is running at 2.8 m/s [forward] when he slides into home plate for a distance of 3.8 m before coming to rest. Calculate the coefficient of kinetic friction. T/I

Forces Applied to Automotive Technology

4.4

Throughout this unit we have addressed automotive safety features such as seat belts and headrests. In this section, you will learn how forces apply to other safety features in cars. Some of these features involve increasing friction with different types of road surfaces. For example, you will learn why different tires are used for specific applications and road conditions, and how antilock brakes and electronic stability controls help drivers maintain control of vehicles on slippery surfaces. Another car safety feature is crumple zones that become crushed when a car collides with another object (**Figure 1**). These different technologies have advantages, but they also have limitations. By understanding the physics involved in these safety features, you will become a safer driver and a more informed car consumer.

Figure 1 A typical crash test

The Physics of Car Tires

In Investigation 4.2.1, you learned that for many pairs of materials the force of static friction or kinetic friction acting on an object is not affected by the amount of surface area in contact with a surface. Instead, the coefficients of friction depend on the types of materials in contact. The magnitude of static friction or kinetic friction only depends on the coefficient of friction and the magnitude of the normal force. However, rubber is an exception. For example, the magnitude of static friction acting on a rubber tire on a road surface depends on the surface area of the tire that is in contact with the road. That is one reason why race cars have very wide tires with no treads. These types of tires are designed to maximize the surface area in contact with the road, which increases the magnitude of static friction acting on the tires, and also dissipates heat more quickly. This, in turn, helps race cars move along curved paths without slipping. If it starts raining during a race, the event is sometimes postponed because these types of tires have no treads.

Unlike race car tires, the tires on passenger vehicles need to provide good traction (force of friction) on road surfaces under all weather conditions. The tread area on a tire has small and large grooves (**Figure 2**). Grooves provide pathways for water, such as rain and snow, to pass beneath the tire as it rolls over a wet road. This helps the tire maintain contact with the road. As a result, the magnitude of friction acting on the tires is usually large enough for safe driving.

When driving at a low safe speed on a wet road, the water level in front of a passenger car tire is low (**Figure 3(a)**). The water has time to move through the grooves in the tire tread and be squeezed out behind the tire. In this situation, friction from the road still acts on the tire. If the driver starts to speed up, some of the water in front of the tire will not have enough time to pass through the grooves toward the back of the tire (**Figure 3(b)**). This causes the water level in front of the tire to increase. This excess water causes the tire to start to lose contact with the road. If the driver's speed continues to increase, the water level in front of the tire will increase to the point where the tire no longer directly touches the road surface (**Figure 3(c)**).

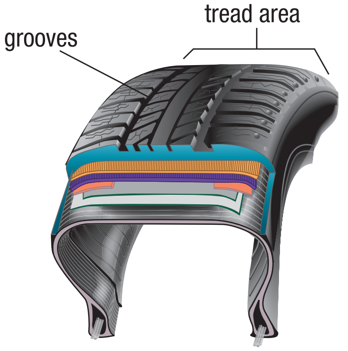


Figure 2 The tread on tires is designed to work under various road conditions. Beneath the rubber tread are layers that provide added safety and strength.

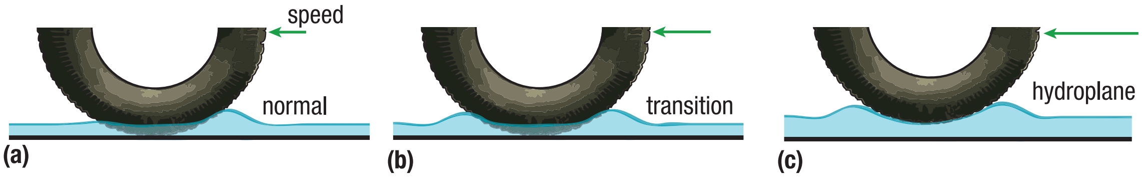


Figure 3 (a) When a car travels at low speeds on a wet road, water levels are low in front of and high behind the tire (the normal stage). (b) If the speed of the car increases, water levels increase in front of the tire (the transition stage). (c) If the speed of the car continues to increase, water levels in front of the tire increase to the point where the tire no longer makes direct contact with the road surface (the hydroplane stage).

Now the tire experiences no friction from the road and very little friction from the water. As you learned in Chapter 3, an object experiencing no net external force will continue to move at constant velocity. The two materials in contact are now rubber and water, not rubber and the wet road. This situation is called hydroplaning and is very dangerous. It results in the driver losing control of the vehicle and being unable to slow down due to the very low friction acting on the tires. The only way to avoid hydroplaning is to drive slowly when the roads are wet.

The tread depth on passenger car tires is usually 7 mm to 8 mm for a new tire. As the tires wear, the tread depth decreases and less water is able to move through the grooves. Driving with worn tires increases the chance of hydroplaning. When the tread depth gets too low, the tires should be changed.

The Physics of Car Brakes

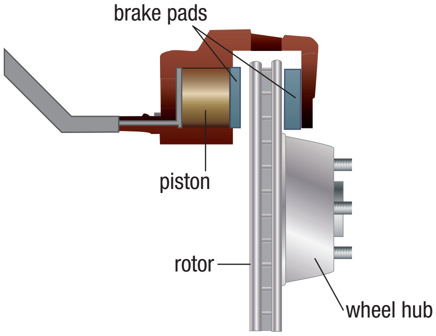


Figure 4 The piston pushes the brake pads against the rotor, creating a force of friction. The friction slows down the wheel.

There is no perfectly safe car crash, but engineers continually work at protecting car occupants as much as possible. Even though vehicles are becoming safer every year, many people across the world still die in car crashes.

The best way to survive an accident is to avoid one. Nothing will ever replace sensible driving at the proper speed. However, sooner or later every driver gets into a situation where an accident might occur. One safety feature found in many cars is antilock brakes. A disc brake on a car is very similar to the brakes on a bicycle. However, in disc brakes, a piston squeezes the brake pads against a rotor (**Figure 4**). Braking harder increases the magnitude of the normal force, which in turn increases the force of friction acting on the rotor. The rotor is attached to the wheel, and as the rotor slows down so does the wheel.

One problem with disc brakes on cars is that the brake can stop the wheel from turning a lot faster than the friction from the road can stop the car from moving. This results in the wheels becoming locked and sliding across the road. So the car skids and the driver is unable to steer the car. The antilock braking system (ABS) on cars helps solve this problem.

An ABS uses a computer to monitor the readings of speed sensors on the wheels of the car. If a wheel experiences a sudden large decrease in speed, the computer quickly reduces the force on the brake pads until the wheel moves at an acceptable speed again. The computer can change the force on the brake pads very rapidly, which allows the car to slow down as fast as possible without the tires skidding. This helps to slow down the car rapidly while allowing the driver to maintain control and steer the car.

One problem with ABS is that drivers feel a chattering action in the brake pedal when slowing down to avoid an accident. Drivers often think this means something is wrong and lift their foot off the brake pedal or, even worse, start pumping the brakes. However, this chattering action is normal for ABS and drivers should continue to apply firm pressure to the brake pedal. Under no circumstances should the driver pump the brakes in a car with ABS. Pumping the brakes will make the car travel farther before it stops. There is some evidence that ABS technology does not actually improve the safety of car crashes because drivers do not use it properly. In some cases drivers who maintain control due to ABS actually steer off the road to avoid an accident, which often results in more serious injuries.

CAREER **LINK**

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Electronic Stability Controls on Cars

Another safety system on cars very similar to ABS is traction control. Traction control is actually the reverse of ABS. ABS comes into play when a car is slowing down and the tires start sliding on the road. Traction control is used when the car is speeding up, especially when starting from rest, and the tires start sliding. If the driver presses down hard on the accelerator, one or more of the wheels may start turning faster than the car is moving. The force of friction on the fast-turning wheels decreases and the driver can lose control of the vehicle and have an accident.

Traction control involves sensors that detect the sliding tires. This information is sent to a computer, which decreases the amount of fuel to the engine. The computer may even use ABS to slow the wheels down. The main thing is that traction control helps the driver maintain control of the vehicle while accelerating.

Electronic stability control (ESC) uses both traction control and ABS to help increase the safety of a vehicle. The sensor for ESC is usually located at the centre of the car. Its purpose is to detect if the car is tilting too much one way or another when making a sharp turn. The two scenarios where ESC comes into play are when the car is experiencing understeering or oversteering (**Figure 5**). Understeering occurs when the force of friction acting on the front wheels is not enough to prevent the car from travelling in a straight line while the driver is trying to turn. Oversteering is the opposite. When oversteering occurs, the car turns more than the driver intended and the back wheels start to slide sideways, spinning the car around.

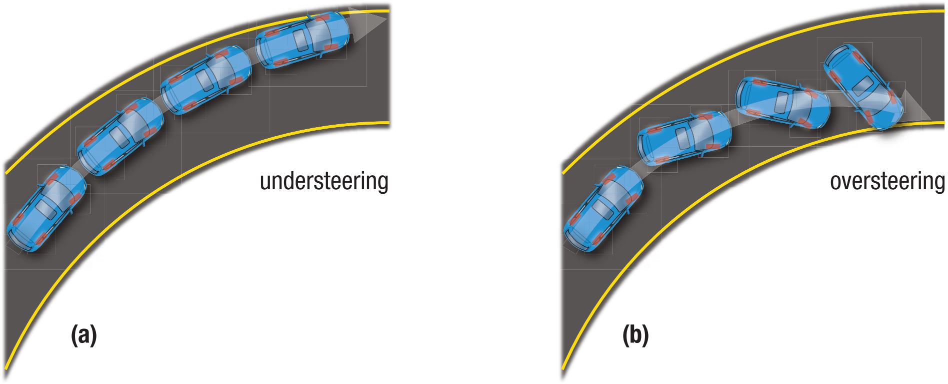

Figure 5 Both (a) understeering and (b) oversteering are dangerous and can cause a car to go off the road or end up hitting another vehicle.

To help prevent both of these situations, ESC can activate one or more brakes using ABS or adjust the speed of the car using traction control. The end result is that the driver has a better chance of controlling the motion of the car with ESC than without it. However, ESC does not actually drive the car for you. Only responsible driving can keep the driver and passengers safe. A driver who is driving too fast or faster than road conditions allow can easily create a dangerous situation, whether the car has ESC or not.

Crash Testing

Crash tests are all about making sure cars are safe and helping to make them even safer. Yet car crashes are still one of the leading causes of death and injury in North America. One of the most important tools used during a crash test is a crash test dummy. A crash test dummy is designed to accurately simulate what will happen to a person during an accident. To collect data during a car crash, the dummy has three different kinds of sensors. The dummy is typically covered with accelerometers that measure the acceleration of different parts, like the head and torso. A motion sensor in the chest measures how much it gets compressed during the crash. This information can be used to estimate the severity of injuries to the torso. Load sensors all over the dummy are used to measure other forces acting on it. This extra information helps engineers determine the nature and severity of injuries.

Seat Belts

Possibly the most important way to protect a person during an accident is to use the seat belt. You have already studied how the seat belt is involved in keeping a person in a car seat. However, early seat belt designs actually caused injuries due to the tremendous force exerted by the belt on the person. Today two design features for seat belts are used to help prevent these types of injuries.

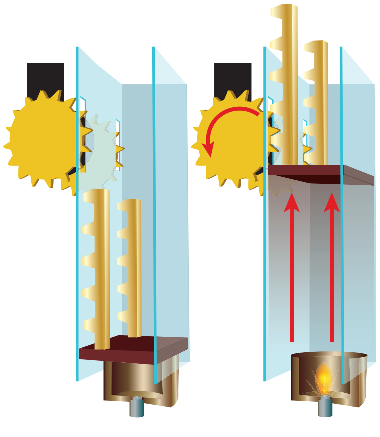

Figure 6 When a computer detects a crash, it ignites the gas in the chamber, which pushes a piston up. A rack gear attached to the top of the piston turns another gear, which pulls in the seat belt.

The first seat belt design feature is called a pretensioner. The pretensioner pulls in on the belt when a computer detects a crash (**Figure 6**). During a sudden stop or a mild crash, the seat belt is reeled in, causing the person to be pulled into the optimal crash position in the seat. This reduces the forces acting on the person and helps keep the person in the car seat. However, if the accident is very violent, the forces exerted by the seat belt on the person may cause serious injury, even if the person is sitting in the optimal position. A safety feature to help in this situation is a load limiter. Load limiters release some of the belt if a tremendous force starts to pull on it. One simple way to do this is to sew a fold into the belt material. When a person in an accident pushes forward on the seat belt with a large force, the stitching breaks and a greater length of seat belt material becomes available. This decreases the force acting on the person. Another way of making a load limiter is to use a torsion bar. This bar keeps the belt in place by restricting the turning of the spool that is used to wind up the belt material. If a large force acts on the belt, the torsion bar can twist slightly, releasing some of the material and reducing the force acting on the person.

Car Body Design

The most noticeable safety feature during a crash test is the crumple zones of the car. At one time, cars were built with rigid frames that were inflexible even during severe accidents. With these cars, drivers and passengers experienced huge accelerations as the car stopped almost immediately during the collision. Crumple zones on cars are designed to crush during an accident. This crushing action increases the time it takes to stop the car during a collision. By increasing the time interval during the crash, the acceleration of the people within the car and the forces acting on those people are significantly reduced. Lower forces mean that it is more likely that the people in the car will survive the accident uninjured.

Another car safety feature involves some parts of the car body being made of plastic. The plastic body parts serve two main purposes during a collision. First, they will not interfere with the crumple zones since plastic is very flexible. Second, the lightweight plastic keeps the mass of the car low enough to make the car easier to stop to avoid a collision.

Airbags

Another car safety feature is airbags. These devices are deployed during a car accident to help prevent the people inside a car from hitting a hard surface like the dashboard or steering wheel (**Figure 7**). A thin nylon airbag is folded in the steering wheel or dashboard. A sensor that detects a collision causes sodium azide to react with potassium nitrate to produce nitrogen gas. The reaction happens so fast that the airbag is pushed out at over 300 km/h. During a car crash, a driver or passenger continues to move forward even though the car comes to a sudden stop. With a deployed airbag, the person collides with the airbag instead of the steering wheel or dashboard. As the person collides with the airbag, it compresses. This increases the time interval of the collision, which further reduces the magnitude of the force acting on the person.

Even when an airbag is deployed, a person can still become injured. If a person is sitting too close to the airbag, the rapidly inflating airbag can cause serious injury to the head and arms. It is for this reason that children should never sit on the passenger seat. Instead, children are more protected from injury when seat belted in the back seat. It is important to keep in mind that a seat belt should be worn at all times, whether or not the vehicle has airbags.

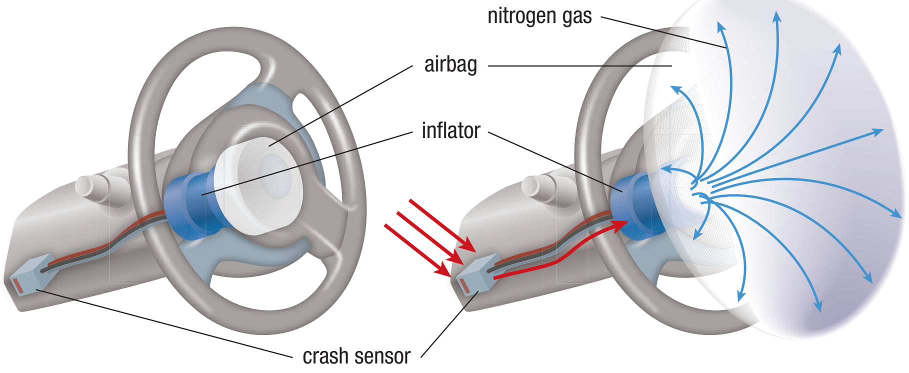

Figure 7 An airbag before and after a collision

4.4 Summary

- The force of friction acting on rubber tires depends on the surface area in contact with a road surface. For most other substances, the force of friction depends only on the coefficient of friction and the magnitude of the normal force.
- Hydroplaning occurs when a tire loses direct contact with the road surface. This situation occurs when a driver is moving too fast on a very wet road.
- The antilock braking system (ABS) uses a computer to adjust the braking on each car wheel to prevent the wheels from locking up. This helps a driver maintain control of a vehicle when slowing down quickly.
- Electronic stability control (ESC) uses both ABS and traction control to help prevent oversteering or understeering.
- The crumple zones of a car are designed to crush during an accident. The crushing action increases the time it takes the car to come to a stop during the collision. This longer time interval, in turn, decreases the magnitude of both the acceleration and the forces acting on the people inside the car.

UNIT TASK **BOOKMARK**

You can apply what you have learned about forces and automotive technology to the Unit Task on page 204.

4.4 Questions

1. Tire X has treads 8 mm deep. Tire Y has the same design but the treads are 2 mm deep. A
   (a) Which tire is more likely to experience hydroplaning when driving on a wet road? Explain your reasoning.
   (b) What happens to the force of friction acting on the tire as the surface area decreases during the transition stage of hydroplaning? Explain your reasoning.
2. In **Figure 8**, the red marks show where tire wear has occurred for improperly inflated tires. Describe what effect, if any, these wear patterns might have on a car travelling on a wet road. C A

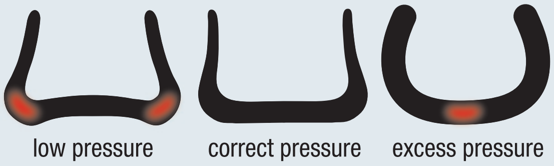

Figure 8

3. Describe what happens to the water levels near a tire as it travels on a wet road at ever-increasing speeds. Explain how these water levels affect the force of friction acting on the tires. K/U
4. Compare the disc brake on a car to the brakes on a bicycle. How are the two braking systems different? A
5. Some stationary exercise bikes have a control that adjusts the amount of friction on the wheel. T/I C A
   (a) What is the purpose of this device?
   (b) Describe a possible design for this device. Include a diagram in your description.
   (c) Describe how you would perform an investigation to determine the relationship between the setting on the control and the maximum force of static friction acting on the wheel.
6. Explain how disc brakes work in terms of forces and Newton's laws. K/U
7. Discuss the validity of the statement, "Car brakes slow the wheels down but friction from the road slows the car down." Explain your reasoning and give examples to support your arguments. C A
8. Explain how ABS helps to achieve each result listed below, even though it periodically reduces the friction on the wheel. K/U
   (a) reduce the stopping distance
   (b) help the driver maintain control of the car
9. (a) Compare and contrast ABS and traction control.
   (b) Explain how and when ESC uses ABS and traction control. T/I
10. Explain how crumple zones help to reduce the force on people inside a car during an accident. K/U
11. Describe two new safety innovations involving seat belts. K/U
12. (a) What is the purpose of an airbag?
    (b) Explain how an airbag works.
    (c) Explain how airbags help protect people in cars during a collision. K/U
13. Tires are rated according to their traction, temperature, and tread wear. Research this rating system and briefly describe the meaning of each rating characteristic. T/I C

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4.5 Forces Applied to Sports and Research

Newton's laws of motion and the principles of gravity and friction are involved in many activities and technologies all around us. Some of these applications involve reducing forces, such as Teflon coatings on frying pans or applying wax to skis or snowboards. Others involve increasing forces, as in the design of golf clubs (**Figure 1**) or running shoes. In this section, you will learn about many new applications for forces in sports and research. To understand these applications, you will use everything you have learned in this unit.

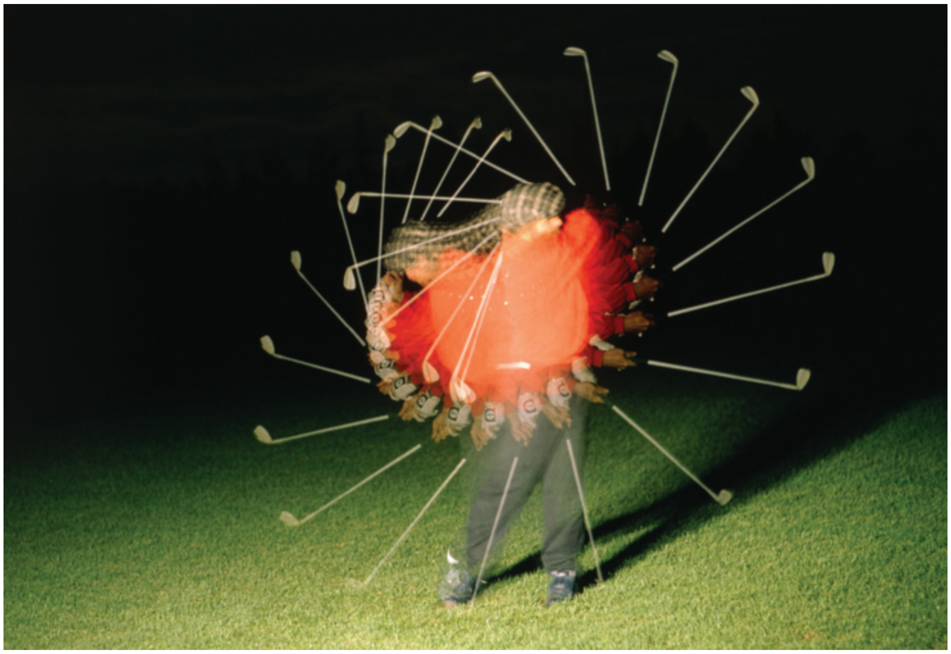

Figure 1 A stroboscopic photograph of a typical golf swing. What forces are involved in making the golf ball move as far as possible?

Forces Applied to Sports

In many different sports, there are times when you want to increase forces and other times when you want to decrease forces. We will examine a few examples of these applications of forces.

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Golf Club Design

In many sports, a player has to move a ball or puck as quickly as possible by striking it. In volleyball, basketball, and football, players use their arms to do this. In soccer, players use their legs. In hockey, cricket, baseball, and golf, players use another object such as a stick, bat, or club. Here we will examine the physics of a typical golf club.

The typical golf swing for a long-distance shot involves making the head of the club hit the ball as fast as possible without twisting the head of the club. The faster the club head is moving when it strikes the ball, the farther the ball will travel. However, if you swing the club harder, it does not always work. If the centre of the head (called the sweet spot) does not make contact with the ball, the head may twist and the ball will travel in the wrong direction. A better-designed club can typically increase distance and control, but it cannot make an inexperienced golfer into a good one.

The different parts of a golf club are shown in **Figure 2**. The grip is made of either leather or rubber. Its purpose is to increase the force of static friction acting on the player's hands, increasing control. The shaft connects the grip to the head and is made

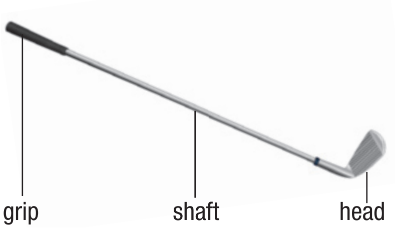

Figure 2 The parts of a golf club

of steel or a carbon-fibre resin composite. The carbon fibre is lighter but more expensive. The length of the shaft varies with the type of club. Clubs that are designed to move the ball over long distances have a longer shaft and are called woods. Clubs that are meant for shorter distances have shorter shafts and are called irons. The shafts vary in stiffness as well. A less flexible shaft is meant for players who can move the club quickly. More flexible shafts are meant for players who tend to whip the head of the club around to gain speed. The head of the club is the part that makes direct contact with the ball. Heavier heads tend to twist less when they hit the ball off centre, but they are harder to swing and hit the ball more slowly.

In other sports, a player must also use good technique to hit a ball or puck as fast as possible, as in the case of a good hit in baseball, a hard shot in hockey, or a hard spike in volleyball. In the end, a better hockey stick helps, but nothing replaces skill and practice.

Footwear Design

In many sports, the footwear worn by an athlete is just as important as any other piece of equipment used in the game. Sometimes the footwear is designed to decrease the force of friction, as with skates. At other times, the frictional forces must be increased to help athletes stop and start quickly, as with running shoes.

The coefficient of kinetic friction of a skate blade on ice may be as low as 0.005, when the ice is perfectly smooth. Physicists thought that this very low coefficient of friction was due to a very thin layer of water forming between the blade and the frozen ice. They thought that the pressure of the skate pushing down on the ice caused the ice to melt, making it more slippery. Physicists now know that this is only a factor when the ice is at exactly 0 °C. Ice that is colder than 0 °C will not become more slippery due to this effect.

Physicists have found that a thin liquid layer of slushy water exists naturally on the surface of ice rinks. It is this slushy layer that reduces the coefficient of kinetic friction. The layer is usually very thin (10^{-8} m) and it gets thinner as the ice is cooled. At –25 °C, the slushy layer does not exist at all, and the coefficient of kinetic friction of a steel skate blade on ice is 0.6, which is comparable to most other coefficients of friction. Modern skate blades are slightly curved at the bottom (**Figure 3**). This allows the skater to dig the edge of the blade into the ice and use the normal force to push forward when accelerating.

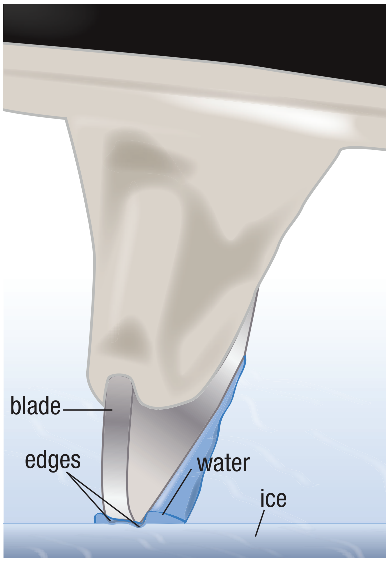

Figure 3 A layer of slushy water that forms between the bottom of a skate blade and the ice reduces the force of friction. The bottom of the blade is curved to help a skater dig into the ice to accelerate.

Running shoes are designed to increase the force of static friction exerted by the ground on the athlete. This allows the athlete to accelerate at greater rates. This design is extremely important in sports where quick starts and stops are required. It also helps an athlete have greater manoeuvrability. Running shoes are also designed to protect ankles and knees from injuries during strenuous activities. They are also designed to be as light as possible to reduce weight and help increase speed.

The typical design of a running shoe is shown in **Figure 4**. The bottom tread of the shoe (called the outsole) is made from a durable carbon-rubber compound to help increase the coefficient of static friction. The midsole is made from foam to help reduce the magnitude of forces acting on the ankles and knees as a person is running. The inner part of the midsole is often made of a harder material to provide stability, while the outer part is made of a softer material to help cushion the impact. It is not unusual for the magnitude of the normal force to triple during various sports activities. The cushion helps absorb some of this impact. Some midsoles include air or gels to help further absorb the impacts when running.

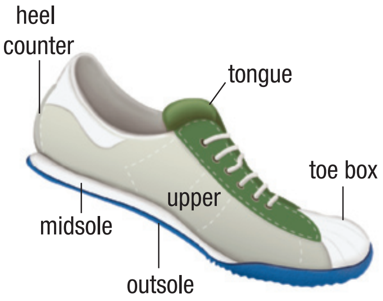

Figure 4 The parts of a running shoe

The upper part of the shoe is designed for comfort and to decrease movement of the foot within the shoe. The heel counter is a hard cup-shaped device used to promote stability and the movement of the heel. The forces exerted by an athlete on the ground while running can be very large in magnitude, but from Newton's third law, a force of equal magnitude is exerted by the ground on the feet in the opposite direction. The best running shoes allow an athlete to quickly accelerate, while at the same time absorbing some of these forces to protect the athlete from injury.

Bearing Design

One way to reduce friction and increase efficiency of devices such as generators, motors, and fans is to use bearings. Bearings are devices that allow surfaces to slide or roll across each other while reducing the force of friction. Many different types of bearings can be used under different circumstances. A plain bearing involves sliding two surfaces across each other while they are lubricated with oil or graphite. A rolling element bearing uses balls or rollers to reduce friction (**Figure 5**). The balls or rollers are usually lubricated with oil. Both of these types of bearings have been used for years and can have very low coefficients of friction.

Some newer types of bearings can reduce friction to negligible levels in some cases. For example, fluid bearings use a film of fluid, such as air or oil, to separate two surfaces (**Figure 6**). The fluid film reduces the force of friction drastically in a similar way that a thin layer of water separates a skate blade on ice. Fluid bearings require a seal to keep the fluid in place and a pump to replace the fluid when it leaks. These bearings can be made cheaply, and they create less noise when operating than rolling element bearings. However, they can fail suddenly without warning if the seal breaks. These types of bearings also use energy to keep the lubricant in place. A typical use for fluid bearings is in the hard drive of a computer.

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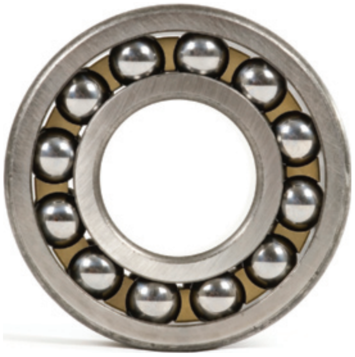

Figure 5 A typical rolling element bearing

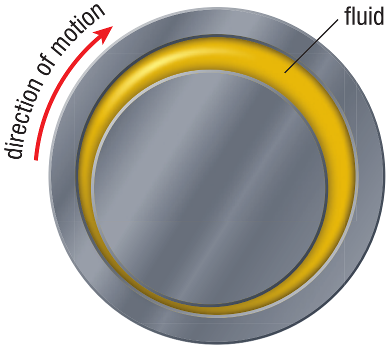

Figure 6 A typical fluid bearing

Magnetic bearings use magnetic fields, instead of fluids, to keep two surfaces separated. The two surfaces do not make direct contact with each other, so this technology is often called magnetic levitation. Magnetic bearings often require a backup bearing system in case they fail. Electricity is required to operate the electromagnets that keep the surfaces separated. So energy is required to keep the bearings working. However, the bearings need no maintenance and have no known upper limit on speed. Typical uses of magnetic bearings are in motors, turbines, generators, Maglev trains, and household meters.

Forces Applied to New Innovations

One area of interest in current physics involves the design of artificial limbs. Another area of current research is in developing materials that have very low coefficients of friction.

Prosthesis Design

A prosthesis is an artificial device that replaces a missing body part. This application of forces involves replacing parts of the body that have been damaged by accident or disease or are the result of birth defects. These artificial body parts could be dentures, hip replacements, heart valves, or even artificial hearts. In this section, we will examine artificial limbs.

Artificial limbs have seen many recent improvements, involving new materials that are lighter, more durable, and more flexible than previous materials. Some claim that these new materials and designs actually give an amputee a physical advantage over other athletes. For example, a newly designed artificial leg is lighter and stronger than a human leg. This might allow an athlete to run faster and longer than they normally could. For example, Oscar Pistorius of South Africa (**Figure 7**) was not eligible to compete in the 2008 Summer Olympic games because it was believed that his artificial legs gave him an unfair advantage. The ruling was eventually overturned; however, Oscar did not end up qualifying. He did very well, though, in the Paralympics.

The design of artificial limbs has progressed even further. Scientists and engineers are working on making them look and act more like real limbs. One technique involves targeted muscle reinnervation (TMR). This method uses a robotic arm or leg that is connected to different muscles in the body. When the patient thinks about moving the artificial limb, the muscles contract and the sensors detect the contraction, making the limb move. The U.S. Pentagon's research division, Defense Advanced Research Projects Agency (DARPA) is funding work on connecting the artificial limb directly to the human nervous system.

The Proto 1 is the prototype that uses TMR to control an artificial mechanical arm (**Figure 8**). These artificial limbs are designed for people who have lost a limb. The Proto 1 can complete tasks previously thought impossible by a mechanical arm. The arm can perform complex tasks such as taking a credit card out of a wallet or stacking cups using sensory feedback from the arm rather than vision. One of the main advantages of this type of arm over other similar devices is the ability to closely monitor the force of the grip of the hand and to easily make adjustments to the amount of force.

New designs are expected to have greater degrees of freedom and behave even more like a human arm. The next Proto design will have 80 different sensors that provide feedback about touch, position, and even temperature.

CAREER **LINK**

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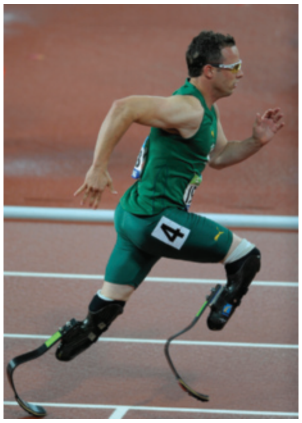


Figure 7 Oscar Pistorius has been referred to as the "blade runner" from South Africa.

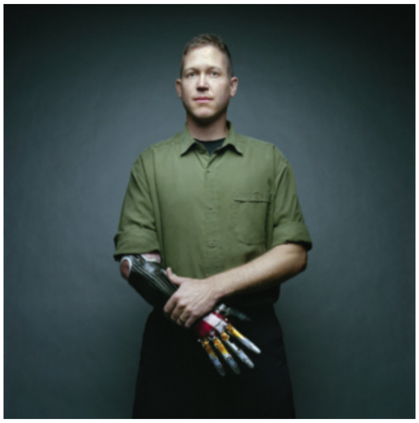


Figure 8 The Proto 1 mechanical arm

Near-Frictionless Carbon

One of the major problems in mechanical devices is wear and loss of efficiency due to friction. At one time, Teflon seemed to be the answer to this problem. Teflon has a low coefficient of friction and can be used as a coating on non-stick frying pans and pots to help reduce the amount of oil required when cooking. However, near-frictionless carbon is now the frontrunner in the race to produce a solid substance with the lowest coefficient of friction.

Near-frictionless carbon has a coefficient of friction less than 0.001, whereas Teflon has a coefficient of 0.04 when tested under the same conditions (**Figure 9**). The coating of near-frictionless carbon is very hard and resists wear from sliding and rolling. It can be applied to many different types of surfaces and reduces the need to replace and repair moving parts in many different types of machines. High-tech applications are being researched in the space program and in aircraft design, for example. However, any type of bearing could make use of this new carbon coating. This technology may eventually become cheap enough to be used in automobiles and compressors such as air conditioners.

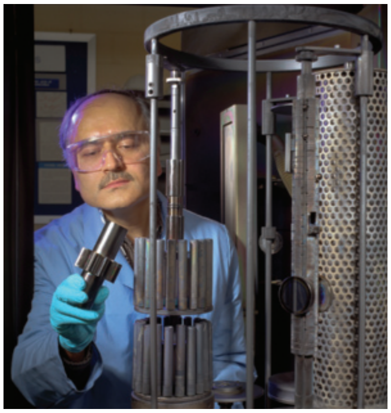


Figure 9 A researcher examining a coating of near-frictionless carbon

4.5 Summary

- The study of forces can be applied to improve sports technology.
- Bearings are used to decrease the force of friction and improve efficiency.
- New research into innovations with forces involves fields of study such as prosthesis design and materials such as near-frictionless carbon.

4.5 Questions

1. The physics involved in striking a golf ball and making it move as fast as possible is similar in many ways to the physics involved in striking a puck or ball in many other sports. K/U A
   (a) Describe how a spike in volleyball is similar to hitting a golf ball.
   (b) How is a slapshot in hockey similar to striking a golf ball?
2. A baseball bat has a sweet spot when it strikes a baseball. K/U T/I A
   (a) What does the term "sweet spot" imply about the motion of the ball after the swing?
   (b) Research what happens to the motion of the bat and the batter if the ball hits the bat at positions other than the sweet spot.
3. Examine the typical golf swing in **Figure 1** on page 184. What evidence do you have from this photograph that the golfer is using good technique when striking the golf ball? K/U
4. At one time physicists thought that the blade of a skate pushing down on the ice created a thin layer of slushy water that decreased the force of friction acting on the blade. K/U
   (a) Explain why physicists now know this is not true.
   (b) Why do skates actually slide so easily over ice?
   (c) Why will blades not slide easily over extremely cold ice?
5. The Therma Blade uses a small battery to heat the skate blade when the player is on the ice. This type of skate blade experiences significantly less friction than a normal hockey blade. T/I C A
   (a) Explain why the Therma Blade experiences less friction than a normal hockey blade on ice.
   (b) A battery must be inserted into the hollow plastic above the top of the blade. Why might this be considered a disadvantage?
   (c) Research the Therma Blade. Describe how it works and its current level of use. Discuss the advantages and disadvantages of the blade.
   (d) In your opinion, should the Therma Blade be allowed in hockey leagues across Canada? Explain your reasoning.
6. The ancient Egyptians used rolling logs to move large blocks of stone when building the pyramids. How is the physics of a rolling element bearing similar to this ancient method of reducing friction? A
7. (a) Describe a typical fluid bearing, and explain how it reduces the force of friction acting on two surfaces.
   (b) Compare the physics of a fluid bearing to that of the blade of a skater on ice. K/U
8. (a) Describe how a magnetic bearing works.
   (b) What disadvantages do magnetic bearings have over rolling element bearings? K/U
9. Some people with artificial limbs want to compete with athletes in the Olympics and in other sports events. C A
   (a) Give three reasons why this should be allowed and even encouraged.
   (b) As technology improves, artificial limbs may provide a significant advantage to people using them. Should professional athletes using artificial limbs be allowed to compete with those who do not use these limbs? Explain your reasoning.
10. There has been some debate recently that some people might wish to replace properly working parts of the body with prostheses. This may become more prevalent as the technology begins to improve and prostheses become better at performing tasks than the actual human body. T/I A
    (a) Research some of the new advances in prostheses.
    (b) How do you feel about this possible trend in the use of this technology? Should governments get involved with this issue? What kind of legislation should be passed, if any? Explain your reasoning.
11. A common use of prostheses today is the artificial hip. What characteristics do you think the materials used in a hip replacement must have to be able to function properly? A
12. Describe the properties of near-frictionless carbon and discuss how it might be used in the future. K/U

GO TO NELSON SCIENCE

4.6 Explore an Issue in Forces

Mandatory Snow Tires in the Winter?

SKILLS MENU

- Defining the Issue
- Researching
- Identifying Alternatives
- Analyzing
- Defending a Decision
- Communicating
- Evaluating

It is a typical winter morning in Ontario, with many people getting into their cars and leaving for work. Fresh snow has fallen overnight, and the roads are covered in a thick blanket of snow. The snowplows have not yet cleared the roads. So people are forced to make their way through the snow-covered highways and streets. A common sight is a car off the side of the highway stuck in the snow (**Figure 1**).

Many accidents like this could be prevented by drivers changing their driving habits during bad weather conditions. Just slowing down and driving more carefully can help. Some drivers think that changing their tires to snow tires during the winter months can also drastically reduce accidents.

In Ontario, all-season tires and snow tires are the two main types of tires used on vehicles (**Figure 2**). Some drivers use their all-season tires year round. Others switch between all-season tires and snow tires. Snow tires are used when the temperature gets colder and there is a chance of snow or ice covering the roads. These tires are marked at stores with a special symbol (**Figure 3**). This, of course, means that car owners must buy two sets of tires for each car. In addition, if you do not want to pay the cost of changing the tires on your rims every year, it also means that you have to buy an extra set of rims. The extra set of rims allows for easier installation every time you change the tires.

Figure 1 A car that has lost control on a snow-covered road

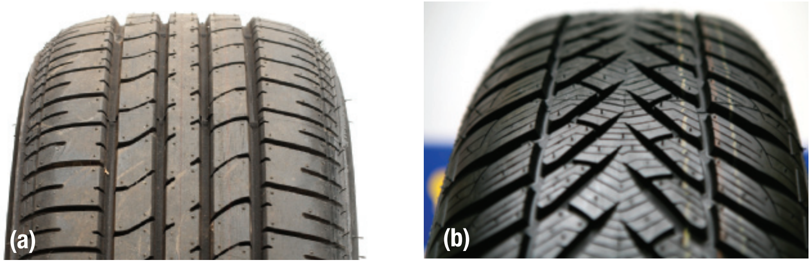


Figure 2 Typical treads on (a) a snow tire and (b) an all-season tire

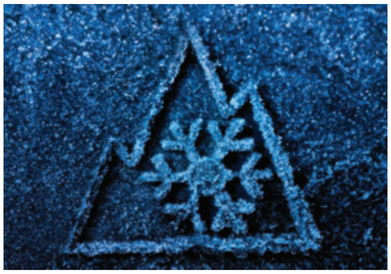


Figure 3 This logo is placed on any new snow tire that has met the required performance standards for snowy conditions.

Many people in Ontario think that all-season tires are suitable for all weather conditions and can be used year round. They also think that the added expense of another set of tires and rims is not worth the money, and that many people cannot afford it. Some people even go as far as to claim that snow tires are just a marketing tool or scare tactic used to increase tire sales. Others believe that snow tires are essential for winter driving. They think that these tires make a drastic difference in winter driving and the extra cost is outweighed by the improvement in safety. Others claim that snow tires should be mandatory for all vehicles in Ontario during the winter months.

As of 2008, from November 15 to April 15, all drivers in Quebec must put snow tires on their vehicles or risk being fined. The fines can be very expensive, but the police often have trouble spotting vehicles without snow tires. Jean-Marie de Koninck, the head of a Quebec task force on road safety, claimed that before the mandatory snow tire law was passed about 10 % of drivers did not use snow tires but were involved in 38 % of the vehicle accidents during winter.

The Issue

The Ontario government is considering passing a law making snow tires mandatory for all cars and trucks on the road. This means all company and personal vehicles must use snow tires during the winter months.

ROLE

You have been assigned to an Ontario task force to research the advantages and disadvantages of using snow tires versus all-season tires in Ontario during the winter. Part of your task is to investigate the differences in the two types of tires: the difference in performance in cold, snowy, and icy conditions; and whether or not they are useful in a typical Ontario winter. You will be required to produce a report on the subject that includes what scientific evidence you have gathered, your reasoning, and your recommendations.

AUDIENCE

You will present your findings to the government and citizens of Ontario.

Goal

To decide whether a law should be passed in Ontario making snow tires mandatory

Research

Work in pairs or in small groups to learn more about the performance of all-season tires and snow tires during the winter. Consider opinions, as well as scientific evidence, on this issue. Research these questions:

- What is the range of temperature where each type of tire is most effective?
- How different are the treads on these two types of tires?
- How do the tires compare in stopping distance when a vehicle stops on ice or snow?
- Are all-wheel-drive vehicles another option instead of using snow tires? What about traction control?
- Are all-season tires a viable option that can be used safely all year round?
- What are some disadvantages of using each type of tire?
- How much does the average snow tire cost? Should cost of the tires be a factor in the decision? 🌐

WEB **LINK**

To learn more about all-season and snow tires,

🌐 GO TO NELSON SCIENCE

Identify Solutions

Is a new law required in Ontario to make snow tires mandatory during the winter months? Can a compromise be reached? If so, what is the compromise and how will it be implemented? Can drivers just replace two all-season tires with two winter tires?

Make a Decision

What does your task force recommend? Explain how you reached your decision.

Communicate

Complete a presentation of your findings that can be shared with the public. State your recommendations with your reasons. Remember that most of your target audience are not engineers or scientists but consumers and government officials. However, these people will make the final decision on whether or not to proceed with your recommendation.

Plan for **Action**

Now that you have an opinion about using snow tires in Ontario, have a talk with your family to help them decide if they should purchase snow tires. Write one or two paragraphs outlining what you would say to your family members to make them more informed about the issue.

Investigation 4.1.1 CONTROLLED EXPERIMENT

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Acceleration Due to Gravity and Terminal Speed

In this investigation, you will drop different objects and measure the acceleration of each object. You will then study objects that are affected by air resistance to a greater degree and investigate the concept of terminal speed.

Testable Questions

(a) What is the acceleration due to gravity at your location?

(b) What factors, if any, affect the acceleration due to gravity?

Hypothesis/Prediction

SKILLS HANDBOOK A2.2

After reading through the Experimental Design and Procedure, write a hypothesis for the Testable Question given in (b) above. Your hypothesis should include predictions and reasons for your predictions.

Variables

Identify the controlled, manipulated, and responding variables in this experiment.

Experimental Design

There are two possible methods of performing this investigation. One uses a motion sensor and the other uses a ticker tape timer. Your teacher will let you know before you begin which procedure you will use. You will attach a motion sensor to a retort stand and drop two different objects below the sensor. Another method involves using a similar setup with a ticker tape timer (**Figure 1**).

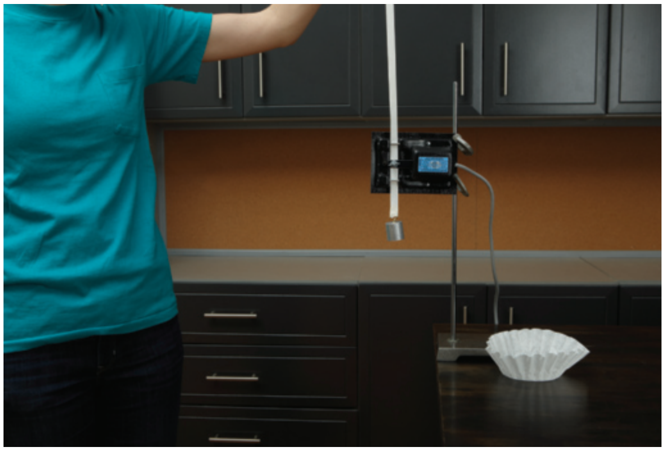


Figure 1

Equipment and Materials

- ticker tape timer or motion sensor
- retort stand
- clamp
- two objects (one 50 g and the other 100 g)
- coffee filter

Procedure

Part A: Acceleration Due to Gravity

1. Set up the equipment as shown in **Figure 1**. If you are using ticker tape, make sure that the tape will not catch on anything as the object falls.

Take care to not drop the objects near your feet. Pick up the objects immediately after dropping them.

2. Drop the 50 g object and obtain the data necessary to find its acceleration. Repeat with the 100 g object.
3. Drop all three objects (50 g, 100 g, and coffee filter) at the same time, and observe which one(s) land first. Record your observations. If you are using a motion sensor, graph the falling motion of the coffee filter.

Part B: Simulating Free Fall

4. If you have access to a program that can simulate an object in free fall, use it to examine the velocity of a falling object with a large mass. If possible, vary the mass of the object and observe the effect of mass on the terminal speed. Also, change the cross-sectional area of the object without changing its mass, and determine the effect of cross-sectional area on terminal speed.

Analyze and Evaluate

(a) Answer the Testable Questions. T/I C

(b) In terms of the variables in this experiment, what type of relationship was being tested? T/I

(c) Calculate the acceleration of the 50 g and 100 g objects from your data. What effect does the mass of an object have on the acceleration due to gravity? T/I

(d) Compare the motion of the coffee filter to that of the other two masses. Explain why the motion is different. T/I

(e) List some possible sources of error. What could be done to reduce these sources of error? T/I

(f) Comment on the validity of your hypothesis. C

Apply and Extend

(g) Describe the velocity–time graph for an object in free fall for an extended period of time. What happens to the acceleration of the object during free fall? Why does this happen? T/I

(h) What effect would each situation below have on the terminal speed of an object? T/I

- increase the mass but keep the cross-sectional area the same
- increase the cross-sectional area but keep the mass the same

Investigation 4.2.1 CONTROLLED EXPERIMENT

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Factors That Affect Friction

In this investigation you will design and perform several controlled experiments where you will measure $F_{S_{max}}$ and F_K acting on an object. To measure the forces you can use a spring scale or a force sensor. To get meaningful results, complete each measurement several times and use an average value, rather than a single measurement.

Testable Question

How does each factor affect the magnitude of friction acting on an object?

- the mass of the object
- the size of the contact area of the object with a surface
- the smoothness of the contact area and of the surface
- the types of materials in contact with each other

Hypothesis/Prediction

SKILLS HANDBOOK A2.2

After reading through the experiment, write a hypothesis to answer the Testable Question. Your hypothesis should include predictions and reasons for your predictions.

Variables

Identify the controlled, manipulated, and responding variables in this experiment.

Experimental Design

Use these questions to help you design your procedure:

- Is the value of $F_{S_{max}}$ different from F_K? If so, which is greater?
- How does the mass of an object affect F_K acting on the object? Does mass affect $F_{S_{max}}$?
- How does the contact area of the object affect either $F_{S_{max}}$ or F_K?
- How do the types of materials in contact with each other affect both $F_{S_{max}}$ and F_K?

In your group, decide how you will test each question. Your teacher will tell you if you are to test all the questions or only a few. Write out the steps in your procedure and prepare any data tables that you will need. List any safety precautions.

Take care not to drop the objects near your feet.

Equipment and Materials

- spring scale or force sensor
- balance
- blocks of wood or other materials
- various objects of different mass
- string

Copy this list and add to it any other materials needed.

Procedure

When your teacher has approved your procedure, carry out the experiment.

Analyze and Evaluate

(a) Answer the Testable Question. T/I C

(b) In terms of the variables in this experiment, what type of relationship was being tested? T/I

(c) How does the value of $F_{S_{max}}$ compare to F_K? T/I

(d) Plot a graph of F_K versus m. What is the relationship between these two variables? Does a similar relationship exist between m and $F_{S_{max}}$? Explain your reasoning. T/I C

(e) Did the value of either $F_{S_{max}}$ or F_K change significantly when you changed the contact area? T/I

(f) List some possible sources of error. What could be done to reduce these sources of error? T/I

(g) Comment on the validity of your hypothesis. C

Apply and Extend

(h) Why should you use the greatest force required to start an object moving to measure $F_{S_{max}}$? T/I

(i) To measure the kinetic friction, you could pull an object at a constant velocity. Use Newton's laws to explain why the force measured by the spring scale or force sensor is equal to F_K. T/I

(j) When determining F_K, why is it better to use the average force reading when pulling the object at a constant velocity rather than a maximum force reading? T/I C

(k) In this experiment, why was it important to repeat your measurements several times for each factor and use average values rather than a single measurement? T/I

Investigation 4.2.2 CONTROLLED EXPERIMENT

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Coefficients of Friction

Coefficients of friction are determined by experiments rather than by calculations. In this investigation, you will measure $F_{S_{max}}$ and F_K for a wood block being pulled on several different surfaces. You will then apply the equations for static and kinetic friction to determine the coefficients of friction in each situation. The applied force acting on the block should always be parallel to the surface.

Testable Question

How does the roughness of a surface affect the coefficient of static friction and the coefficient of kinetic friction for a block of wood, and how do these coefficients compare with each other?

Hypothesis/Prediction

After reading through the experiment, write a hypothesis to answer the Testable Question. Your hypothesis should include predictions and reasons for your predictions.

Variables

Identify the controlled, manipulated, and responding variables in this experiment.

Experimental Design

You will use a spring scale or a force sensor to pull a wood block horizontally along various horizontal surfaces of your choice (**Figure 1**).

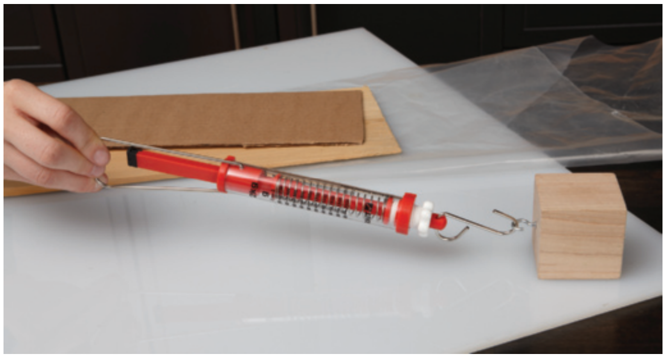


Figure 1

To measure the maximum magnitude of static friction acting on the block, slowly increase the applied force on the spring scale or force sensor. The greatest reading before the object starts to move is the maximum magnitude of static friction. To measure the magnitude of kinetic friction, use the average reading required to pull the block slowly at a constant velocity across the surface.

Equipment and Materials

- balance
- spring scale or force sensor
- block of wood
- various flat surfaces of different materials such as wood, metal, or plastic ramps; a desktop; a floor; sheets of plastic
- string

Procedure

1. Make a table with these headings: Surface, $F_{S_{max}}$, and F_K.
2. Measure the mass of the block of wood.
3. Using the first surface, measure the maximum magnitude of static friction three separate times by slowly increasing the applied horizontal force as you pull the spring scale or force sensor. Record the results in your table.
4. Using the same flat surface, pull the block at a slow constant velocity across the surface with the spring scale or force sensor. Use the average reading for the magnitude of kinetic friction. Repeat the measurement two more times. Record the results in your table.
5. Repeat Steps 3 and 4 for two other surfaces. Try to use one surface you think might exert a low force of friction on the block and at least one that might exert a high force of friction.

Analyze and Evaluate

(a) Answer the Testable Question. T/I C

(b) In terms of the variables in this experiment, what type of relationship was being tested? T/I

(c) For each surface, calculate the average of $F_{S_{max}}$ and F_K acting on the block of wood. Using these values, calculate the coefficient of static friction and the coefficient of kinetic friction. How do these coefficients compare for a particular surface material? T/I

(d) Did the coefficients of friction change when the block was placed on a different surface? T/I

(e) List some possible sources of error. What could be done to reduce these sources of error? T/I

(f) Comment on the validity of your hypothesis. C

Apply and Extend

(g) Would it make sense if a student claimed that their data showed that the coefficient of kinetic friction was greater than the coefficient of static friction? Explain your reasoning. T/I

Investigation 4.3.1 OBSERVATIONAL STUDY

Predicting Motion with Friction

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

In this investigation, you will calculate the acceleration of a system of objects given the total mass of the system and the coefficient of kinetic friction for the system. You can determine the coefficient of kinetic friction for a surface and block of wood.

You will use a ticker tape timer, a motion sensor, or a similar device to record the motion of the wood block as shown in **Figure 1**. Before you perform the investigation, you will first calculate the acceleration using Newton's laws. Then you will compare the calculated value to the acceleration that you measure from the investigation.

Purpose

To determine how friction affects the acceleration of the system shown in Figure 1.

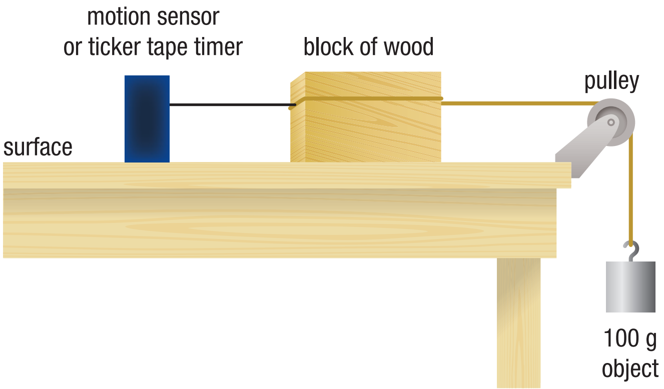


Figure 1

Equipment and Materials

- ticker tape timer or motion sensor
- balance
- pulley
- spring scale or force sensor
- block of wood
- flat surface such as a wood, metal, or plastic ramp or a desktop
- 100 g object
- string

Procedure

1. Set up the equipment as shown in Figure 1. Let the 100 g object pull on the block to make sure that the system is starting from rest. Release the block to see if the system accelerates. If it does not, hang additional objects from the string until you see that the system accelerates when you release the block.

Take care not to drop the objects near your feet.

2. Measure the mass of the block of wood. Record the total mass that is hanging from the string. Remember that the sum of all the masses will give you the mass of the system.
3. Determine the coefficient of kinetic friction using a spring scale or force sensor.
4. Calculate the acceleration of the system using the known information and Newton's laws. Assume that the system is starting from rest. This will be your calculated acceleration. If you have access to a simulation program, set up a simulation to check your calculations.
5. Perform the experiment and obtain the data necessary to measure the acceleration.

Analyze and Evaluate

SKILLS HANDBOOK A6.2

(a) Determine the acceleration of the system from the data gathered in the experiment. T/I

(b) Calculate the percentage error for the actual and calculated accelerations. T/I

(c) List some possible sources of error. What could be done to reduce these sources of error? T/I

Apply and Extend

(d) What effect would each situation have on the acceleration of the system? T/I

- placing another object on top of the wood block
- increasing the mass that is hanging from the string

Explain your reasoning. If time permits, test each situation and comment on your results.

CHAPTER 4 SUMMARY

Summary Questions

1. Use the Key Concepts in the margin on page 160 to create a study guide for this chapter. For each point, create three or four subpoints that provide further information, relevant examples, explanatory diagrams, or general equations.
2. Look back at the Starting Points questions on page 160. Answer these questions using what you have learned in this chapter. Compare your latest answers with those that you wrote at the beginning of the chapter. How have your answers changed?

Vocabulary

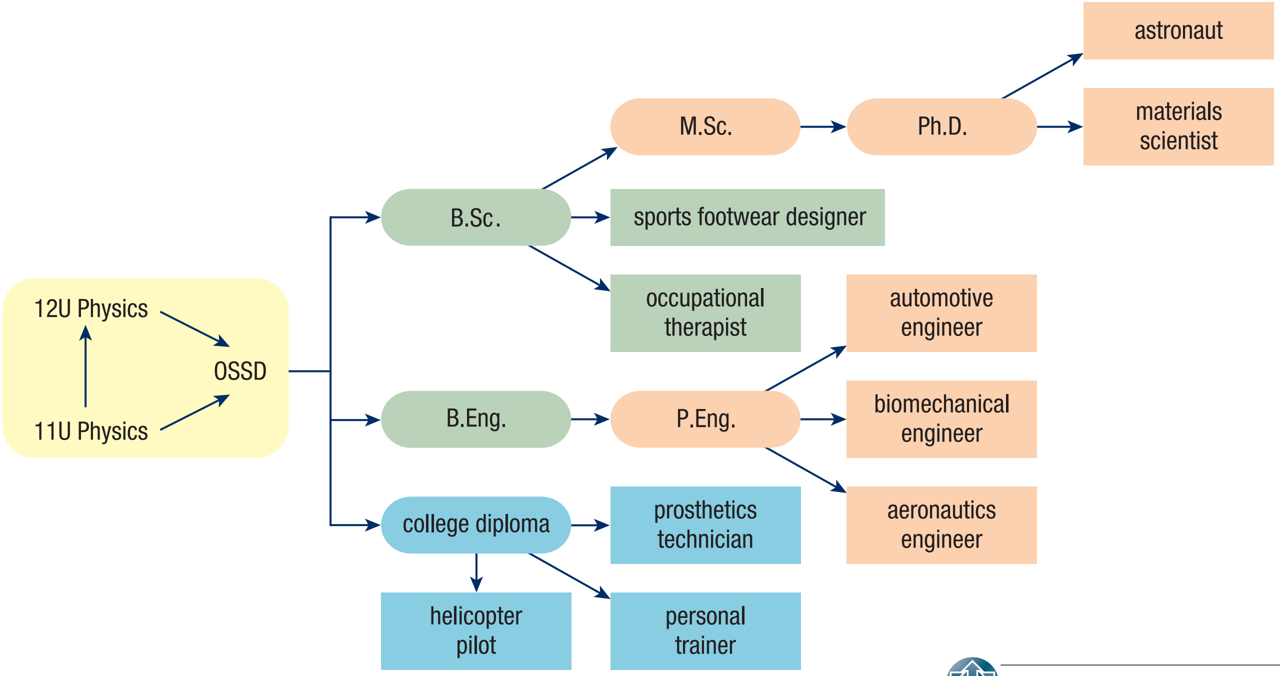
free fall (p. 162)
terminal speed (p. 163)
force field (p. 164)
gravitational field strength (p. 164)
static friction ($\vec{F}_S$) (p. 168)
kinetic friction ($\vec{F}_K$) (p. 168)
coefficient of friction (μ) (p. 169)
coefficient of static friction (μ_S) (p. 169)
coefficient of kinetic friction (μ_K) (p. 169)

CAREER PATHWAYS

SKILLS HANDBOOK A7

Grade 11 Physics can lead to a wide range of careers. Some require a college diploma or a B.Sc. degree. Others require specialized or post-graduate degrees. This graphic organizer shows a few pathways to careers related to topics covered in this chapter.

1. Select an interesting career that relates to Applications of Forces. Research the educational pathways you would need to follow to pursue this career. What is involved in the required educational programs?
2. What is involved in becoming a prosthetics technician? Are there different pathways you could take to this career? Research at least two programs and summarize your findings in a brief report.



12U Physics
11U Physics
OSSD
B.Sc.
B.Eng.
college diploma
M.Sc.
Ph.D.
astronaut
materials scientist
sports footwear designer
occupational therapist
P.Eng.
automotive engineer
biomechanical engineer
aeronautics engineer
prosthetics technician
helicopter pilot
personal trainer

GO TO NELSON SCIENCE

CHAPTER 4 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. Regularly timed pictures of a ball falling at terminal speed will have what type of spacing? (4.1) K/U
   (a) erratic
   (b) even
   (c) uneven
   (d) increasing
2. Compared to slow-moving objects, fast-moving objects experience
   (a) no air resistance
   (b) less air resistance
   (c) equal air resistance
   (d) more air resistance (4.1) K/U
3. The magnitude of gravitational field strength is equal to the magnitude of the
   (a) speed of free fall
   (b) gravitational acceleration
   (c) static friction coefficient
   (d) gravitational force (4.1) K/U
4. Kinetic friction force depends on the normal force acting on an object and which of the following? (4.2) K/U
   (a) coefficient of static friction
   (b) speed of motion
   (c) direction of motion
   (d) coefficient of kinetic friction
5. Which of these is an example of static friction making an object move? (4.3) K/U
   (a) a runner pushing off starting blocks
   (b) a car coming to a controlled stop
   (c) a plate being pushed across a table
   (d) a sliding box decreasing in speed
6. Which of these are the two friction surfaces in an automobile disc brake? (4.4) K/U
   (a) piston and rotor
   (b) pads and piston
   (c) piston and wheel hub
   (d) pads and rotor
7. Running shoes are designed to do what to the force of friction between the runner and the ground? (4.5) K/U
   (a) increase
   (b) decrease
   (c) slow down
   (d) all of the above
8. Near-frictionless carbon is a proposed solution for problems of both friction and
   (a) space
   (b) weight
   (c) wear
   (d) speed (4.5) K/U

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

9. Free fall is when both gravity and air resistance are acting on a falling object. (4.1) K/U
10. The force of air resistance on an object depends on several factors, including the object's cross-sectional area. (4.1) K/U
11. When an object is sliding, it experiences a greater magnitude of friction force than when it is stationary. (4.2) K/U
12. Kinetic friction is the force exerted on an object by a surface that prevents a stationary object from moving. (4.2) K/U
13. Sometimes friction is desirable. (4.3) K/U
14. If the force produced by a train engine is not large enough to overcome the combined static friction of the cars, it will move some of the cars. (4.3) K/U
15. Usually friction does not depend on the contact area, but rubber is an exception. (4.4) K/U
16. Electronic stability control uses traction control, but not an antilock braking system. (4.4) K/U
17. When airbags are deployed, the driver of the vehicle cannot become injured. (4.4) K/U
18. Magnetic bearing systems do not require backup bearings because they do not fail. (4.5) K/U
19. Some claim that new materials and designs used in prosthetics actually give athletes with artificial limbs an advantage over other athletes. (4.5) K/U
20. Near-frictionless carbon has a coefficient of friction greater than that of Teflon. (4.5) K/U

To do an online self-quiz,
GO TO NELSON SCIENCE

CHAPTER 4 REVIEW

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

Knowledge

For each question, select the best answer from the four alternatives.

1. What is the value of acceleration due to gravity near Earth's surface? (4.1) K/U
   (a) 9.8 N
   (b) 9.8 m/s
   (c) 9.8 m/s^2
   (d) 9.8 km/h
2. Once a skydiver has accelerated to a constant speed, the skydiver is said to be travelling at
   (a) constant acceleration
   (b) terminal speed
   (c) maximum acceleration
   (d) final speed (4.1) K/U
3. The photo shown in **Figure 1** demonstrates that the ball
   (a) continues to accelerate as it falls
   (b) slows down as it falls
   (c) travels at a constant speed as it falls
   (d) neither speeds up nor slows down as it falls (4.1) K/U

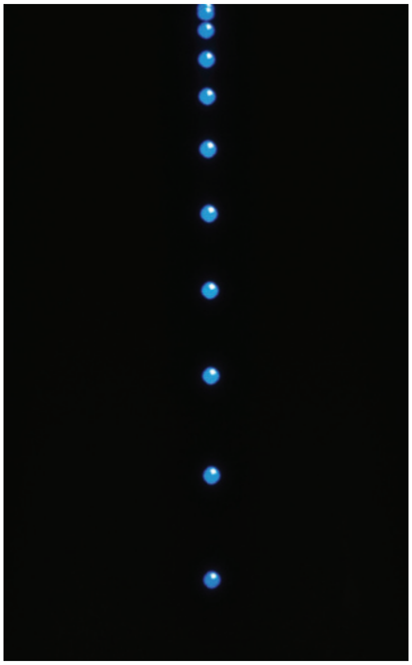


Figure 1

4. An object is said to be in free fall when which of these forces is acting on it alone? (4.1) K/U
   (a) rolling friction
   (b) wind friction
   (c) magnetic force
   (d) gravitational force
5. Compared to an object with a large cross-sectional area, an object with a small cross-sectional area will experience
   (a) less air resistance
   (b) more air resistance
   (c) the same amount of air resistance
   (d) negligible air resistance (4.1) K/U
6. A coin and a feather of equal mass are dropped at the same time. Which will hit the ground first? (4.1) K/U
   (a) the feather
   (b) the coin
   (c) They will hit the ground at the same time.
   (d) Each one has an equal probability of hitting first.
7. The coefficient of friction between two materials is defined by the ratio of the magnitude of the friction force to the magnitude of which other force? (4.2) K/U
   (a) gravitational force
   (b) kinetic force
   (c) static force
   (d) normal force
8. You push on an object, but it does not move. Which force are you unable to overcome? (4.3) K/U
   (a) gravitational force
   (b) kinetic friction
   (c) static friction
   (d) normal force
9. An object is given an initial push, is released, and slides along a surface. While it is sliding, kinetic friction will cause the object to
   (a) maintain its speed
   (b) increase its speed
   (c) decrease its speed
   (d) conserve its speed (4.3) K/U
10. Hydroplaning occurs when the water level in front of the tires is
    (a) too low to pass through the tires' grooves
    (b) low enough for the water to pass through the tires' grooves
    (c) high enough to pass through the tires' grooves
    (d) too high to pass through the tires' grooves (4.4) K/U
11. Which piece of athletic footwear is designed to decrease friction? (4.5) K/U
    (a) running shoes
    (b) baseball cleats
    (c) ice skates
    (d) basketball shoes

Match each statement on the left with the most appropriate description on the right.

12. (a) The skydiver jumps out of the plane.
    (b) The skydiver speeds up while falling.
    (c) The skydiver falls at a constant speed.
    (d) The skydiver slows due to the parachute.

    (i) Gravity is greater than air resistance.
    (ii) Gravity is less than air resistance.
    (iii) Gravity is the only force acting on the skydiver.
    (iv) Gravity is equal to air resistance. (4.1) K/U

Write a short answer to each question.

13. What is the definition of a force field? (4.1) K/U
14. The terms *mass* and *weight* are often used interchangeably in everyday speech. This is incorrect. (4.1) K/U
    (a) Which term represents a force?
    (b) Which term does not depend on gravity?
15. Define static friction in your own words. (4.2) K/U
16. A force large enough to overcome static friction is applied to an object. What type of force replaces static friction after the object begins to move? (4.2) K/U
17. Many people incorrectly assume friction always acts to reduce the net force on an object. Describe how a car's braking system uses friction to increase the net force on a car as it stops. (4.3, 4.4) K/U C
18. (a) In a paragraph, describe the similarities and differences between an antilock braking system and electronic traction control.
    (b) Explain how an electronic stability control system uses both of these as an overall safety system. (4.4) T/I C A

Understanding

19. Two objects of different mass are dropped from the same height. (4.1) T/I
    (a) If they both hit the ground at the same time, which has a larger cross-sectional area?
    (b) If they have the same cross-sectional area, which will hit the ground first?
    (c) Describe what would happen if the objects were dropped in a vacuum (without the presence of air resistance).
20. (a) What two forces act on a ball dropped through the air?
    (b) As the ball is initially dropped, which force is acting more strongly?
    (c) As the ball is moving at terminal speed, what is the relationship between the two forces?
    (d) If the ball has a mass of 25 kg, what must the magnitude of the friction force at terminal speed be? (4.1) T/I
21. **Figure 2** is the graph of a skydiver's acceleration. (4.1) K/U T/I C

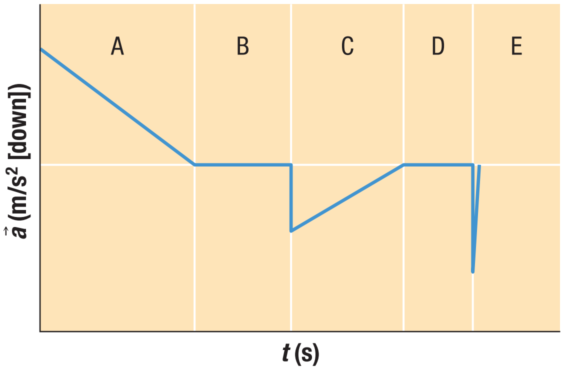


Figure 2

    (a) For each interval of time (A, B, C, D, and E), describe the motion of the skydiver and compare the magnitude of the forces acting on her.
    (b) At which point does the skydiver reach maximum speed?
    (c) At which point is the force of air resistance greatest?
    (d) During which intervals is she travelling at terminal speed?
    (e) Copy Figure 2 into your notebook and plot the skydiver's velocity. You may assume her speed is zero when she leaves the plane.
22. (a) A skydiver slows after the deployment of the parachute. Describe the relationship between air resistance and the gravitational force acting on the skydiver.
    (b) How does this relationship change as the skydiver slows toward terminal speed? (4.1) K/U
23. Compare the magnitudes of the gravitational field strength and the gravitational acceleration at Earth's surface. (4.1) K/U
24. (a) Describe two ways to measure gravitational field strength.
    (b) The force of gravity acting on a 1.50 kg object is 14.67 N. What is the gravitational field strength at that altitude above Earth's surface?
    (c) Is this altitude likely above or below sea level? Explain. (4.1) T/I

25. The weight of an object is measured at three locations: the North Pole, the equator, and the peak of Mount Everest. (4.1) T/I
    (a) Where will the object have the greatest weight?
    (b) Where will the object have the least weight?
    (c) Create a table listing the weight of an object with a mass of 12.687 kg at each of these locations.
26. (a) Define mass.
    (b) How is it possible to change the mass of an object?
    (c) Define weight.
    (d) How is it possible to change the weight of an object, but not change its mass?
    (e) Describe a situation in which the magnitudes of an object's weight and mass are equal. (4.1) K/U
27. (a) Explain why the terms *weightlessness* and *microgravity* are misapplied when discussing astronauts aboard the International Space Station.
    (b) What is the appropriate term to describe the state that makes objects appear to float within the space station? (4.1) K/U
28. A 60.0 kg person is standing on a bathroom scale inside an elevator. The scale is calibrated in newtons. What is the reading on the scale if the elevator is accelerating downward at 1.6 m/s^2? (4.1) T/I
29. To test the forces acting on a person during an amusement park ride, a student sits on a bathroom scale calibrated in kilograms while on the ride. Before the ride starts moving, the reading on the scale is 58 kg. Calculate the reading on the scale when the person is
    (a) moving at a constant velocity of 8.0 m/s [down]
    (b) accelerating at 2.7 m/s^2 [up]
    (c) accelerating at 3.8 m/s^2 [down] (4.1) T/I
30. Describe the difference between static friction and kinetic friction. (4.2) K/U
31. A box, sitting on a horizontal plane, is being pushed by a force that is not able to move the box. (4.2) T/I C
    (a) What forces act on the box?
    (b) Draw a free-body diagram of the box.
    (c) If the mass of the box is 7.5 kg, what is the magnitude of the normal force acting on the box if it is at sea level?
32. An object is being pushed along a horizontal surface with force F_a. Assume the only forces acting on the object in the horizontal direction are F_a and the friction force F_f. (4.2) T/I
    (a) Compare F_a and F_f if the object is slowing.
    (b) Compare F_a and F_f if the object is being pushed at a constant velocity.
    (c) Compare F_a and F_f if the object is speeding up.
33. An object experiences a friction force, F_f, of 6.6 N and a normal force, F_N, of 30.0 N. (4.2) K/U
    (a) What is the coefficient of friction, μ?
    (b) Is the object moving? How do you know?
34. A block of steel weighing 15 N sits on a dry, horizontal steel surface. (4.2) T/I
    (a) Refer to Table 1 on page 170. What force is initially required to make the steel block start sliding across the horizontal surface?
    (b) Once the block has begun sliding, what force is required to maintain the block sliding at a constant speed?
35. Friction occurs between all surfaces we are in contact with in our daily life. (4.2) K/U C
    (a) Describe an example of static friction that you might experience.
    (b) Describe an example of kinetic friction that you might experience.
    (c) Explain how each example of friction either helps something move or stops it from moving.
36. A 4.4 kg object is being pushed along a surface, causing it to accelerate at a rate of 1.5 m/s^2. The coefficient of kinetic friction is 0.25. What is the magnitude of the horizontal force being applied to push the object? (4.3) K/U
37. (a) A couch weighing 620 N is to be pushed to a new location across the room. The coefficient of static friction between the couch and the floor is 0.31. What is the minimum force required to set the couch in motion?
    (b) The coefficient of kinetic friction between the couch and the floor is 0.21. To maintain the couch moving at a constant speed, what force is required? (4.3) T/I
38. At a construction site, one worker passes a brick to another by pushing it across a piece of wood. The brick has a mass of 2.7 kg. The force required to start the brick moving is 18 N. What is the maximum coefficient of static friction between the brick and the wood? (4.3) T/I
39. (a) Rubber is an exception to which concept described for most other materials?
    (b) How does this difference affect the design of car tires? Give an example. (4.4) K/U
40. Explain, with respect to the interactions among the tire, water, and the road, the difference between a car moving at a controllable speed on wet pavement and a car hydroplaning on wet pavement. (4.4) K/U C

41. Car brakes can be broken down into components of a friction problem. Use this analogy to answer the following questions: (4.4) A
    (a) The friction force is applied to which component attached to the wheel?
    (b) The component attached to the wheel experiences a friction force by coming into contact with which other component?
42. Explain how crumple zones in a car's body and frame relate to the force and acceleration experienced by passengers of a vehicle during a collision. (4.4) K/U
43. What embarrassing scenario unfolds when the static friction between a golfer's hand and the golf club is lower than the force of the club's swing, and what do golf club manufacturers do in order to reduce the likelihood of this event? (4.5) A
44. Many applications of physics require a reduction in friction to meet acceptable levels of efficiency for the mechanism to work correctly. Some examples of this are motors, generators, fans, and even vehicles. (4.5) K/U
    (a) What types of bearings have been used for years to facilitate this friction reduction?
    (b) Name a newer type of bearing that reduces friction to negligible levels.
    (c) What are the benefits and tradeoffs of using a magnetic levitation–style bearing?
    (d) What new materials technology allows for both a very low coefficient of friction and a very hard wear surface, and what are some proposed applications for this technology?
45. Two large books are stacked on top of each other on a table (**Figure 3**). The mass of each book is 6.5 kg. Given that the coefficient of static friction between the bottom book and the table is 0.15, what is the lowest the coefficient of static friction between the books can be in order to apply force and move both books? (4.3) T/I

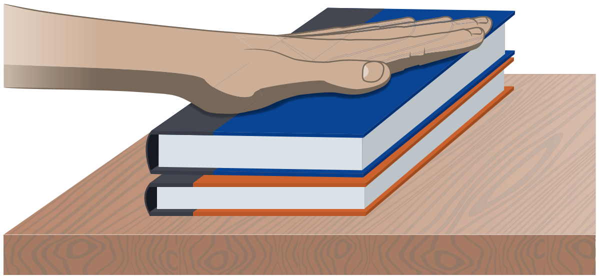


Figure 3

Analysis and Application

46. (a) Using your understanding of gravity and the relationship between force and acceleration, explain why you might feel heavier when an elevator travels upward and lighter when it travels downward.
    (b) Describe another situation in which someone might encounter a similar combination of accelerations to those in an elevator. (4.1) C A
47. Newton used a diagram similar to **Figure 4** to explain how a cannonball could be put into orbit around Earth. Explain how this diagram shows that the cannonball is actually in free fall. Which of the trajectories shown is the fastest? Explain your reasoning. (4.1) T/I A

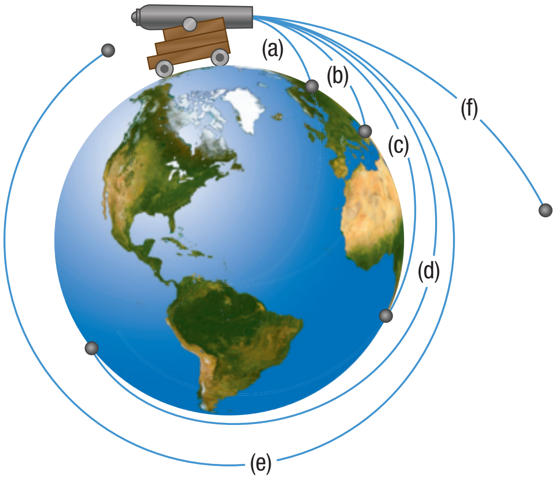


Figure 4

48. Some people think that if a surface is polished to the point where it is very smooth, it can be made virtually frictionless. **Figure 5** shows a metal surface that appears smooth to the unaided eye. Describe what this photograph reveals about friction. (4.2) T/I A

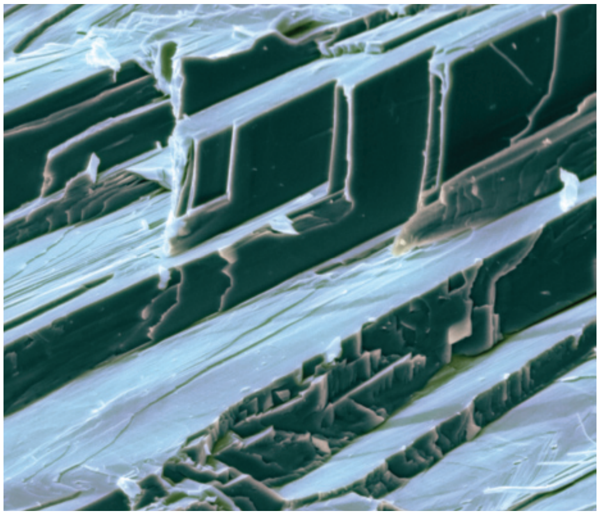


Figure 5

49. A block is pushed across a horizontal surface with a coefficient of kinetic friction of 0.15 by applying a 150 N horizontal force. (4.3) T/I A
   (a) The block accelerates at the rate of 2.53 m/s^2. Find the mass of the block.
   (b) The block slides across a new surface while experiencing the same applied force as before. The block now moves with a constant speed. What is the coefficient of kinetic friction between the block and the new surface?
50. Two sled racing teams use the same sled, but have different dogs and different amounts of equipment. The coefficients of friction are those of steel on ice ($\mu_S = 0.1$, $\mu_K = 0.01$). (4.3) T/I A
   (a) Team 1 pulls a 170 kg sled with 230 N of force and team 2 pulls a 195 kg sled with 250 N of force. Which team will have a quicker start?
   (b) Imagine a situation where each team's dogs are barely able to overcome the force of static friction. When the sleds do start to move, they continue pulling with the same force. How will the accelerations of each sled compare?
51. Sometimes static friction can be used to cause motion instead of impeding it. Running is an example of using static friction to cause motion. Broomball is a game made harder by the small amount of friction available to run, since players are required to wear shoes on ice. (4.3) T/I A
   (a) If a shoe on ice has a coefficient of static friction of 0.05, what is the maximum acceleration a 75 kg broomball player can expect to create?
   (b) If that same player were on a concrete surface, with a coefficient of static friction of 0.85, what acceleration would be possible?
   (c) What would happen to these values if a player of greater mass were on the same surface?
52. Aside from tread depth, describe another factor that might determine the ability of a car's tire to avoid hydroplaning and explain how it could be improved to decrease risk. (4.4) A
53. Most people think solely of the friction reduction capabilities of ice skates. This is only true along the axis parallel with the length of the skate. What would be the consequences of reducing the friction as much as possible along all the axes of an ice skate? (4.5) A

Evaluation

54. Since gravity on Earth is constant and humans have evolved in it and built civilizations around it, one consideration of future space exploration and colonization is adapting to different gravitational environments. The Moon is probably the most accessible possibility for colonization, but it has a lower gravitational field. (4.1) T/I C
   (a) Discuss some advantages and disadvantages of creating an infrastructure in a lower gravitational field. (Consider buildings, transportation, manufacturing, and so on.)
   (b) The human body is also accustomed to Earth's gravity. Discuss some possible effects on the human body of a lower gravitational field.
   (c) What effects might lower gravitational field strength have on human entertainment and sports activities?
55. Humans are affected by gravitational forces other than Earth's. For instance, the Moon exerts a gravitational force that causes the seas to shift in tidal patterns. (4.1) T/I
   (a) If the Moon were closer to Earth, would the tidal shift be greater or lesser? Why?
   (b) If the Moon had less gravitational pull than it does, what would be the effect on Earth's tides?
   (c) Some planets in the Solar System have multiple moons. Describe how Earth having multiple moons might affect the ocean tides.
56. Write a paragraph discussing how coefficients of friction can be determined experimentally. What forces must be measured to do so? What are some variables that can affect results? How could these variables be controlled or documented and accounted for? (4.2) T/I C
57. Friction is commonly a force that needs to be overcome. However, without friction we would not be able to do many of the things we do on a daily basis. Name one thing that would not be possible without friction, and propose an alternative way to accomplish it without being able to rely on friction. (4.2) C A
58. Friction is a very common source of energy loss. Most often, the friction force converts energy into heat. (4.2) K/U T/I C A
   (a) Explain how this friction loss has an impact on the efficiency of a common item (for example, a car, a computer, a refrigerator).
   (b) Describe some of the ways product designers could try to minimize friction in their products.

59. One challenge faced by engineers is predicting the magnitude of the forces their designs will experience in a real-world application. (4.2, 4.3) T/I C A
   (a) Refer to Table 1 on page 170 to explain how an engineer designing the interaction between two parts of greasy steel might encounter this challenge.
   (b) How might engineers overcome this uncertainty?
   (c) Another example of this uncertainty is discussed in this chapter regarding the design of golf clubs. What are some variables that change the forces experienced by a golf club during its use?

Reflect on Your Learning

60. The creation of tools to take advantage of forces is one of the most characteristic distinctions between humans and other animals. K/U T/I C A
   (a) Explain how one of the discussions in this chapter illustrates how humans are capable of taking advantage of forces such as gravity and friction, and explain how that advantage helps make daily life easier.
   (b) Find another example of technology taking advantage of gravity or friction and explain how it works and how it makes life easier.
61. (a) Before you read this chapter's discussion of mass and weight, what was your understanding of these two terms and their relationship to each other? Was that understanding correct? If not, why?
   (b) Explain why using these terms interchangeably must be avoided in the context of physics and science in general. K/U C
62. Air resistance can be both helpful and challenging to overcome. Most of our encounters with air resistance come when we try to move ourselves at high speed, such as for transportation. Write about a situation in which we use air resistance to our advantage and one situation where we have to use technology to overcome the forces we feel due to air resistance in transportation. In what ways had you been introduced to air resistance before reading this chapter? K/U C A
63. Section 4.4 discusses many safety features in automobiles. What safety features were you aware of in cars before reading about those discussed in this chapter? Should your understanding of these safety features allow you or your friends to drive with less care than you would have without knowing about them? Why? A

Research

GO TO NELSON SCIENCE

64. The list of Newton's contributions to science and mathematics is easily as long as anyone else's in history. Research Newton's law of universal gravitation. Write a report describing the law itself, including the mathematical formula describing the gravitational force between two objects. T/I K/U C
65. While it is generally understood that automobile manufacturers are researching ways in which we can use/produce energy more efficiently, many people are unaware of the fact that these manufacturers are also busy developing ways in which we can recover otherwise wasted energy. One of these energy recovery methods is known as regenerative braking. Regenerative braking is a way to recover energy lost in standard friction-based brake systems. Research regenerative braking and write a report about it. You may wish to discuss how regenerative braking works and its current and future applications. T/I K/U C A
66. The idea of a parachute can be shown to have been developed over 500 years ago by none other than Leonardo da Vinci. Research the history of the parachute. Write a short report detailing the timeline of the parachute from the days of da Vinci to the present day. Be sure to discuss any major technological advances or historical milestones. T/I C
67. Guillaume Amontons was the first to publish laws of friction. His laws stated that the friction force is proportional to the normal force acting on the object and independent of the area of contact. Research the life of Guillaume Amontons, noting his other scientific contributions. Write a short biography that highlights significant moments in his personal and public life, along with his major scientific breakthroughs. T/I C
68. Adding to Amontons's laws of friction, Coulomb's friction law stated that the kinetic friction force is independent of sliding velocity. Charles-Augustin de Coulomb is also known for his contributions to the realm of electricity. Research Coulomb's life and write a biography. Be sure to include a discussion of his major scientific contributions and their impact on the scientific community. T/I C
69. Thermal energy is, very often, an unwanted by-product of friction. When thermal energy is the desired effect, however, friction can be a useful way of providing it. This is the case with the development of the friction match. Research the friction match and write a report describing how it works and how it went from an invention to an everyday household object. K/U C

Egg Crash Test

In this unit, you have studied forces and how they are related to technology. Some of the technological applications have dealt with vehicles and vehicle safety. One of the most important tests performed on a vehicle is the crash test. In each crash test, a dummy is placed inside the vehicle to help engineers determine any vehicle safety issues that may occur during a crash.

The Task

In this task, you will perform a similar test, except that you will use an egg instead of a crash test dummy and a dynamics cart instead of a vehicle (**Figure 1**). The egg must be attached to the front of the cart and yet remain unbroken after the crash. You will design a device that can start the cart moving from rest and have a reliable way to determine the velocity of the cart upon impact. Higher marks will be awarded for greater velocities upon impact, greater total mass on impact, and an undamaged egg.

Figure 1

Equipment and Materials

Many different materials can be used for this task. You can probably find most of the materials at home. Below are some suggestions:

- dynamics cart or similar toy vehicle
- force sensor or motion sensor
- ruler
- metre stick
- scissors
- egg or other fragile object
- construction paper
- cardboard
- balsa wood
- tape
- glue

Procedure

Part A: Design

1. You may use a dynamics cart provided by your teacher or a similar toy vehicle. The rules for the cart design are as follows:
    - The egg must be attached to the front of the cart, and the cart must make full contact with the wall or barrier during the collision.
    - You may build a bumper-like structure or any other device to help lessen the forces acting on the egg during impact, but you cannot toughen up the eggshell by covering it or chemically treating it.
    - The egg should be easy to insert and remove from the bumper.
    - Consider your skills and safety while designing your bumper.
2. Design a method of launching the cart so that it will hit the wall with a predictable velocity. To do this, you may design a device that is simple or more elaborate, but it should provide consistent velocities with all trials.
3. Design your procedure. You must have a procedure that you can use to determine the velocity of the cart just before striking the barrier.
4. Develop a procedure for analyzing the net force acting on the cart during the collision (if you are using a force sensor or motion sensor).

5. Make a flow diagram showing the steps you used to build the bumper.
6. Draw a diagram of your bumper with labels showing how it will work and how the egg will be inserted.
7. Draw another diagram showing how you will launch the dynamics cart.
8. Before attempting to build any of your ideas, you must first present the design ideas to your teacher.

- Use only tools that you are comfortable with, or get help from someone more experienced.
- Check with your teacher before using any tool in the lab.
- Take care to not drop the cart near your feet.

9. Keep a log of the ideas you tested and any scores that you calculated. You can include diagrams or brief explanations of the steps used.

Part B: Performing the Crash Test

10. Perform three trials of your crash test bumper design. The first trial should involve a lower-velocity collision, and the last two should be higher-velocity collisions. Record the velocity of the cart. Your score will be calculated using the trial that has the least significant damage to the egg.
11. Determine your score by multiplying the velocity of the cart by the mass of the cart and by the damage factor. An egg with absolutely no damage gets a score of 3, an egg with minor cracking a score of 2, an egg with major cracking but still intact 1, and all others get 0.

Analyze and Evaluate

(a) Discuss the role of friction on the motion of your cart. T/I C

(b) Describe any difficulties that you encountered during the design and construction of the cart. T/I C

(c) Explain how you solved design and construction problems, and discuss what you could have done differently to improve your crash test score. T/I C

(d) Create a poster that displays the safety features of your bumper, explaining why it works. Include the drawings you created in Part A showing your design and your design procedure. T/I C

Apply and Extend

(e) Examine the flow diagrams of the design procedures used by other groups. Compare your procedure to those used by other groups.

(f) Explain how you could have improved the design of your bumper.

ASSESSMENT **CHECKLIST**

Your completed Unit Task will be assessed according to these criteria:

Knowledge/Understanding

- ✓ Demonstrate knowledge of forces.
- ✓ Demonstrate knowledge of the safety features of vehicles.

Thinking/Investigation

- ✓ Design a cart according to given specifications.
- ✓ Design a procedure for launching a cart and record relevant information.
- ✓ Evaluate the cart design and procedure and modify it as needed to improve performance.
- ✓ Analyze cart performance and evaluate based on performance of other designs.

Communication

- ✓ Prepare a log of designs, test results, and modifications.
- ✓ Communicate design procedure in the form of drawings and a flow chart.
- ✓ Create a poster demonstrating the design, safety features, development, and function of the cart.
- ✓ Demonstrate understanding of design and construction of the cart.

Application

- ✓ Use equipment and materials effectively to design, test, build, and modify the cart.
- ✓ Demonstrate an understanding of how forces can be applied to the design.

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. A person drinks 100 g of water. How much weight has that person gained in doing so? (3.1) T/I
   (a) 0.98 N
   (b) 9.8 N
   (c) 98 kg
   (d) 9.8 kg
2. Which of the following best describes the frictional force? (3.1) K/U
   (a) a force that resists the motion or attempted motion of an object
   (b) a perpendicular force exerted by a surface on an object
   (c) the pull between two objects at a distance
   (d) the force in a string or rope when pulled
3. Which of the following forces is caused by the electric charges of particles? (3.1) K/U
   (a) electromagnetic
   (b) gravitational
   (c) weak nuclear
   (d) strong nuclear
4. Which of the following objects has the least amount of inertia? (3.2) K/U
   (a) a car
   (b) a bicycle
   (c) a motorcycle
   (d) a tank
5. What is the net force experienced by a 20.0 kg object that accelerates at a rate of 4.0 m/s^2? (3.3) K/U
   (a) 80 N
   (b) 60 N
   (c) 800 N
   (d) 5.0 N
6. What is the acceleration of a block that has a mass of 24 kg and experiences a net force of 40 N? (3.3) K/U
   (a) 1.9 m/s^2
   (b) 0.9 m/s^2
   (c) 1.7 m/s^2
   (d) 1.5 m/s^2
7. A child jumps off a skateboard. What can be said of the force of the skateboard pushing on the child? (3.4) K/U
   (a) It is smaller in magnitude than the force of the child pushing on the skateboard and opposite in direction.
   (b) It is equal in magnitude to the force of the child pushing on the skateboard but opposite in direction.
   (c) It is equal in magnitude to the force of the child pushing on the skateboard and in the same direction.
   (d) It is greater in magnitude than the force of the child pushing on the skateboard and opposite in direction.
8. Two blocks, at 4.0 kg and 5.0 kg, are suspended from the ceiling by a piece of string. What is the tension in the string? (3.5) K/U
   (a) 9.0 N
   (b) 88 kg
   (c) 88 N
   (d) 49 N
9. A ball is falling at terminal speed. You take regularly timed images of the ball. How does the spacing between the images of the ball change? (4.1) K/U
   (a) The spacing between the images increases.
   (b) The spacing between the images decreases.
   (c) The spacing between the images is constant.
   (d) The spacing between the images is irregular.
10. Which of the following scenarios will result in the largest amount of frictional force from the air? (4.1) K/U
   (a) a small surface area moving slowly
   (b) a small surface area moving rapidly
   (c) a large surface area moving slowly
   (d) a large surface area moving rapidly
11. In which of the following scenarios is Earth’s gravitational field strength the least? (4.1) K/U
   (a) standing at sea level at the equator
   (b) on top of a mountain near the equator
   (c) in a space station in orbit
   (d) a kilometre underneath a sea bed
12. An object is sliding along an icy surface. The frictional force causing it to slow down depends on which of the following? (4.2) K/U
   (a) the normal force and the coefficient of static friction
   (b) the tension force and the coefficient of static friction
   (c) the normal force and the coefficient of kinetic friction
   (d) the tension force and the coefficient of kinetic friction

13. Which of the following surfaces has the lowest coefficient of kinetic friction? (4.2) K/U
    (a) Teflon
    (b) ice
    (c) steel
    (d) concrete
14. A person is sliding a 12.0 kg block across ice that has a coefficient of kinetic friction of 0.100. How much force does the person need to apply to keep the block moving at a constant rate? (4.3) T/I
    (a) 11.4 N
    (b) 12.2 N
    (c) 11.8 N
    (d) 12.0 N
15. Which of the following best describes how antilock braking systems work? (4.4) K/U
    (a) A computer forces the car to increase the pressure on the brake pads when the car suddenly slows.
    (b) A computer forces the car to release some pressure on the brakes permanently so that the tires are not damaged.
    (c) A computer forces the car to release some pressure on the brake pads for a short period of time before reapplying pressure.
    (d) A computer calculates the exact distance the car needs to stop and applies pressure on the brakes accordingly.
16. Which of the following types of bearings allows for the two surfaces to not make contact by a type of levitation? (4.5) K/U
    (a) ball bearings
    (b) fluid bearings
    (c) magnetic bearings
    (d) gravity bearings

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

17. A system diagram is a simple drawing of an object showing all the forces that are acting on it. (3.1) K/U
18. A gravitational force results when one object is in contact with another object and either pushes it or pulls on it. (3.1) K/U
19. Galileo formulated the modern laws of force and motion that helped define the science of dynamics. (3.1) K/U
20. The electromagnetic force is an example of an action-at-a-distance force. (3.1) K/U
21. A car will have less inertia than a bicycle if the car is moving fast. (3.2) K/U
22. An object can travel in circles even if the net force the object experiences is zero. (3.2) K/U
23. A force of 100 N will accelerate a mass of 10 kg at 10 m/s^2. (3.3) K/U
24. If the acceleration of an object is increasing, then either the net force the object is experiencing is increasing or the mass of the object is decreasing. (3.3) K/U
25. When your foot pushes off the floor to walk, the floor is pushing back on your foot but with only half the force. (3.4) K/U
26. In *Principia Mathematica*, Newton predicted that the laws of physics would somehow be able to account for all the fundamental forces. (3.6) K/U
27. When a skydiver has accelerated to the point that the force of gravity pulling down on her equals the force of air resistance pushing up, she has reached Mach speed. (4.1) K/U
28. A force field is a region of space surrounding an object that can exert a force on other objects. (4.1) K/U
29. The coefficient of static friction is the ratio of the frictional force on a moving object to the normal force acting on the object. (4.2) K/U
30. If an object has a mass of 10 kg and experiences a maximum static frictional force of 49 N, then the coefficient of static friction between the object and the surface is 0.4. (4.2) T/I
31. If the coefficient of kinetic friction for a horizontal surface is 0.40, then an object weighing 10 N will require 40 N of force to remain in motion. (4.3) T/I
32. Pushing slightly downward on an object while trying to move it across a horizontal surface will increase the frictional force acting on the object. (4.3) K/U
33. The tread on a tire is designed to help the car maintain contact with the road and create friction, even in stormy weather. (4.4) K/U
34. Like antilock braking systems, traction control is used when the car is slowing down and the tires start skidding. (4.4) K/U
35. Golf clubs are designed with rubber grips to help golfers maintain their grip and prevent the club from flying out of their hands on hard swings. (4.5) K/U
36. All-season tires have a special symbol that distinguishes them from snow tires. (4.6) K/U

Knowledge

For each question, select the best answer from the four alternatives.

1. Which of the following is the SI unit of force? (3.1) K/U
   (a) kg
   (b) N
   (c) m/s^2
   (d) km/h
2. The force exerted on an object by pulling on an attached rope or string is called
   (a) tension
   (b) friction
   (c) normal
   (d) gravity (3.1) K/U
3. You push a box across a floor in the direction E 40° N. In which direction is the friction force acting? (3.1) K/U
   (a) W 40° S
   (b) N 50° E
   (c) N 40° E
   (d) W 50° S
4. Which of the following best describes the normal force that acts on an object? (3.1) K/U
   (a) a force that resists the motion or attempted motion of an object in contact with a surface
   (b) a perpendicular force exerted by a surface on an object in contact with the surface
   (c) the force in the nucleus of atoms that holds protons and neutrons together
   (d) the force between positively and negatively charged objects
5. The force involved when protons and neutrons transform into other particles is the
   (a) weak nuclear force
   (b) strong nuclear force
   (c) gravitational force
   (d) electromagnetic force (3.1) K/U
6. The G-suit and other space suit technologies are designed to do which of the following to help counteract the effects of Newton's first law? (3.2) K/U
   (a) prevent inertia from causing blood to move into the legs by applying pressure to the legs
   (b) prevent the effects of gravity on the body
   (c) use electromagnetic signals to counteract the effects of solar radiation on the wearers
   (d) provide the wearers with hydraulic stabilizers so that they can maintain their balance on the Moon
7. The slope of a net force versus acceleration diagram represents which of the following? (3.3) K/U
   (a) velocity
   (b) mass
   (c) weight
   (d) time
8. Which of the following scientists explored areas such as the nature of gravity and black holes, and showed that even black holes can lose mass through radiation? (3.6) K/U
   (a) Galileo
   (b) Newton
   (c) Einstein
   (d) Hawking
9. Falling objects will stop accelerating at the point at which the force of the air resistance is equal to that of gravity. The speed they reach is called the
   (a) resultant speed
   (b) final speed
   (c) terminal speed
   (d) fall speed (4.1) K/U
10. An object in free fall has which of the following forces solely acting on it? (4.1) K/U
    (a) gravity
    (b) electromagnetic
    (c) friction
    (d) strong
11. An object has a smaller cross-sectional area than another object of similar mass. How will this affect the air resistance it experiences? (4.1) K/U
    (a) The object will experience more air resistance.
    (b) The object will experience the same amount of air resistance.
    (c) The object will experience less air resistance.
    (d) The object will experience negative air resistance.
12. Which of the following terms is used to describe the force exerted by a surface on a stationary object that prevents it from moving? (4.2) K/U
    (a) static friction
    (b) kinetic friction
    (c) coefficient of friction
    (d) normal friction

13. Why does steel on ice have such a small coefficient of kinetic friction when ice is slightly colder than 0 °C? (4.5) K/U
    (a) A thin layer of slushy water exists on the surface of ice.
    (b) The steel is able to melt the ice when it is moving.
    (c) Steel has a repelling property when it gets close to ice.
    (d) When steel gets cold, its surface gets smoother.

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

14. Friction is a force that acts to maintain the motion of an object. (3.1) K/U
15. In the nucleus of an atom, the gravitational force holds together the protons and neutrons. (3.1) K/U
16. Gravity is the only fundamental force that does not have an attraction effect. (3.1) K/U
17. Seat belts use Newton's first law by having an inertial pendulum that locks the seat belt in place when the car suddenly brakes. (3.2) K/U
18. A force of 10 N that acts on a box with a mass of 2.5 kg will accelerate it at a rate of 4 m/s^2 even if there is also a friction force acting on the box. (3.3) K/U
19. Steven Hawking considers Einstein to be the greatest figure in mathematical physics and the *Principia* his greatest work. (3.6) K/U
20. Air resistance acts opposite to the direction of motion if there is no wind. (4.1) K/U
21. On the Moon, both your mass and your weight will decrease. (4.1) K/U
22. For a flat surface, the static frictional force can be determined by multiplying the coefficient of static friction by the mass of an object. (4.2) K/U
23. The static friction from the ground enables you to push off with one foot and accelerate your body in motion. (4.3) K/U
24. Quebec law requires that drivers must put snow tires on their vehicles from November 15 to April 15. (4.6) K/U

Match each term on the left with the most appropriate description on the right.

25.	(a) dynamics	(i) the force caused by the charge of particles
	(b) normal force	(ii) a perpendicular force exerted by a surface
	(c) force field	(iii) the area of a car that is meant to be crushed during a collision
	(d) coefficient of kinetic friction	(iv) an area of physics that explains why objects move the way they do
	(e) electromagnetic force	(v) represents the ratio of kinetic friction to the normal force
	(f) crumple zones	(vi) a region of space surrounding an object that can exert a force on other objects (3.1, 4.1, 4.2, 4.4) K/U

Write a short answer to each question.

26. Place the following objects in order from having the least amount of inertia to having the most amount of inertia: atom, pencil, baseball, car, hockey player, proton, motorcycle. (3.2) K/U
27. Place the following combinations of materials in order from having the least amount of kinetic friction to having the most amount of kinetic friction: wood on dry snow, Teflon on Teflon, rubber on concrete, ice on ice. (4.2) K/U

Understanding

28. Draw a free-body diagram for each situation. (3.1) K/U
    (a) A skydiver has reached terminal speed in free fall.
    (b) A boy pushes horizontally and accelerates a box across a rough floor.
29. Describe in your own words the difference between a system diagram and a free-body diagram. Explain how each is used. (3.1) K/U
30. The following situations describe a student moving a box: (3.1) T/I C
    (a) A student pulls a large box across a smooth floor to the right. Draw the free-body diagram.
    (b) A student pushes a large box across a smooth floor to the right. Draw the free-body diagram.
    (c) Are there any differences between the diagrams in (a) and (b)? Explain.

31. An airplane making a routine trip is flying northward with a horizontal force from the engines of 42 000 N. A wind is blowing to the south and pushes the plane with a horizontal force of 1200 N. What is the net horizontal force on the plane? (3.1) K/U

32. A book sits on a desk. Use Newton's first law to explain why the normal force must be equal to the force of gravity in order for the book to remain at rest when no other forces are acting on it. (3.2) K/U C

33. A moving ballistics cart fires a ball straight up. Use Newton's first law and the concept of inertia to explain why the ball follows an arched path instead of going straight up and down even though the force acting on the ball was vertical. (3.2) K/U C

34. Students are trying to see if they can pull apart a rope they made out of a bunch of vines. The two students on the right are able to pull with forces of 95 N and 87 N, and one of the students on the left is able to pull with a force of 104 N. The rope does not break and the students remain stationary. What is the force that the fourth student is pulling with? (3.3) K/U

35. Use Newton's second law to explain each situation. (3.3) K/U
    (a) Two cars are pushed by an equivalent net force, but one car has more mass. Which car will accelerate faster?
    (b) A person pulls a cart with a constant force while his friends keep loading more boxes onto it. What will happen to the acceleration of the cart?

36. Calculate the net force in each situation. (3.3) K/U
    (a) A sprinter with a mass of 68 kg accelerates at a rate of 2.4 m/s^2.
    (b) A 425 g baseball falls after being hit.

37. For each situation, calculate the acceleration. (3.3) K/U
    (a) A 2200 kg car, starting from rest, accelerates northward while experiencing a net force of 4500 N.
    (b) A skydiver with a mass of 71.2 kg experiences a net force of 245 N upward when she opens her parachute.

38. After a hockey player takes a shot, the puck slows down at a rate of 1.3 m/s^2. The mass of the puck is 175 g. What are the magnitude and direction of the frictional force acting on the puck? (3.3) K/U

39. A little-league player hits a baseball from a tee. The baseball experiences a net force of 8.0×10^3 N [S]. The mass of the ball is 145 g. What is the acceleration of the ball? (3.3) K/U

40. The cart in **Figure 1** has a mass of 0.4 kg and is attached, by a string and a pulley, to a weight that has a mass of 0.20 kg. (3.3) K/U

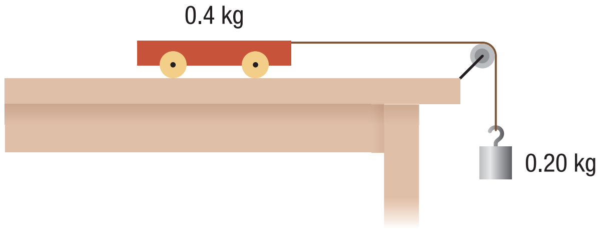


Figure 1

    (a) Calculate the acceleration of the cart, assuming there is no friction.
    (b) Calculate the acceleration of the cart if there is a frictional force of 0.10 N acting on the cart.
    (c) Calculate the magnitude of the tension in the string.

41. Use Newton's third law to explain each situation. (3.4) K/U
    (a) A student jumps off a skateboard, causing it to roll in the opposite direction.
    (b) A person is leaning against a wall and does not move.
    (c) A ball rolls forward, hits a group of balls, and then rolls backwards.

42. A hockey player pushes off the boards with a force of 68 N. The combined mass of the hockey player and her skates is 80 kg. (3.4) T/I C
    (a) Calculate the acceleration of the player as she pushes off if there is a 30 N frictional force from the ice.
    (b) Explain why the boards do not move.

43. A 0.50 kg weight is hanging from a string attached to the ceiling of a helicopter. Calculate the tension in the string for the following situations: (3.5) T/I
    (a) The helicopter is stationary.
    (b) The helicopter is accelerating straight up at 0.80 m/s^2.
    (c) The helicopter is accelerating straight down at 0.92 m/s^2.

44. A small brick is dropped out of a hot air balloon. (4.1) K/U T/I
    (a) What forces are acting on the brick as it falls?
    (b) Which of the forces you listed for (a) is acting more strongly in the instant the brick is dropped?
    (c) Once the brick reaches its terminal speed, what is the relationship between the two forces?
    (d) The brick has a mass of 220 g. What is the force of air resistance acting on the brick when it reaches terminal speed?

45. (a) Describe two different methods that are used to measure the strength of gravitational fields.
  (b) The force of gravity acting on a 2.50 kg object is 24.475 N. What is the gravitational field strength acting on the object?
  (c) For your answer to (b), would this value of Earth's gravitational field strength be likely for an altitude above sea level or below sea level? Explain. (4.1) T/I C

46. (a) In your own words, describe the difference between mass and weight.
  (b) Describe how to change the mass of an object.
  (c) Describe how to change the weight of an object without changing its mass.
  (d) Is it possible for mass and weight to be the same? Explain. (4.1) K/U T/I

47. Two cylinders with different masses are dropped from the top of a building. (4.1) K/U C
  (a) Which one has a larger cross-sectional area if both of them hit the ground at the same time—the lighter one or the heavier one?
  (b) Which one will hit the ground first if they both have the same cross-sectional area?
  (c) Describe what would happen if the objects were dropped in a vacuum (assume there is no air resistance)?

48. An electrician holds a 3.2 kg chandelier up against a ceiling with a force of 53 N. What is the normal force acting on the chandelier from the ceiling? (4.1) T/I

49. A man tries to push a large rock across a flat horizontal surface but is unable to move the rock. (4.2) T/I
  (a) List the forces acting on the rock.
  (b) Draw a free-body diagram of the rock.
  (c) If the rock has a mass of 210 kg, what is the normal force acting on the rock?

50. An object at rest on a flat horizontal surface experiences a maximum static frictional force of 29.89 N. The object has a mass of 5.0 kg. (4.2) K/U T/I
  (a) What is the coefficient of static friction?
  (b) From the materials in **Table 1**, which two could be involved in this interaction?

Table 1

Material	μ_s	μ_k
steel on steel (dry)	0.78	0.42
leather on oak	0.61	0.52
steel on ice	0.1	0.01
Teflon on Teflon	0.04	0.04

51. An ice-fishing hut weighing 52 N sits on a dry, frozen lake. (4.2) T/I
  (a) What is the magnitude of the initial horizontal force required to make the ice-fishing hut start sliding across the surface of the frozen pond?
  (b) Once the ice-fishing hut has begun sliding, what force is required to maintain the hut sliding at a constant speed?

52. A 12 kg box at rest on the floor requires a horizontal force of 47 N to start moving it. Once it starts moving, the same horizontal force makes the box accelerate at 1.1 m/s^2. (4.2) T/I
  (a) Find the coefficient of static friction.
  (b) Find the coefficient of kinetic friction.

53. A runner with a mass of 72 kg is running sprints to train for a track meet. The coefficient of friction between the runner's shoes and the track is 0.79. If the runner starts from rest, what is the maximum rate at which he can accelerate? (4.3) T/I

54. A man is pulling a block with a mass of 6.2 kg across a horizontal surface and accelerates the block at a rate of 0.50 m/s^2. The coefficient of kinetic friction between the block and the surface is 0.24. What is the magnitude of the force with which the man pulls? (4.3) T/I

55. A person pushes a box across a horizontal floor with an initial velocity of 5.2 m/s. The box has a mass of 22 kg, and the coefficient of kinetic friction between the box and the floor is 0.44. How far does the box slide before coming to rest? (4.3) T/I

56. Examine **Figure 2** showing a crash test.
  (a) Describe at least two safety features visible in this photograph.
  (b) Describe the type of information that an engineer would gather during a crash test.
  (c) What evidence is there in the photograph that the crumple zone was very effective in protecting the people in the car? (4.4) T/I C

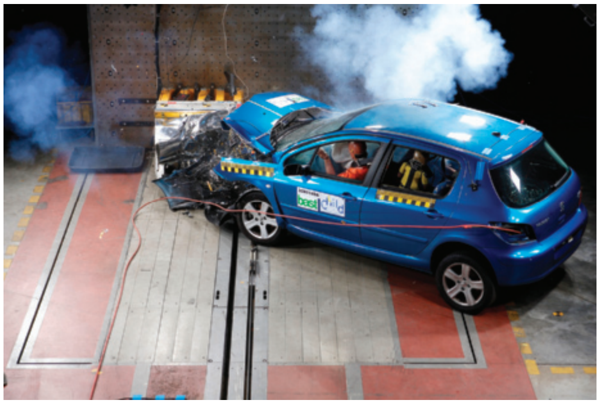


Figure 2

57. A common type of prosthesis today is an artificial hip. **Figure 3** shows a typical design used during a hip replacement. What characteristics do you think the materials used in a hip replacement must have to be able to function properly? (4.5) T/I A

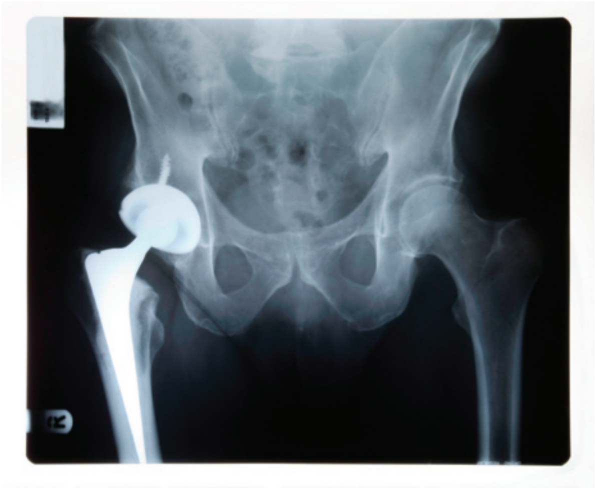


Figure 3

58. In Section 4.6, you researched how snow tires affect the ability of a car to maintain traction on a snowy road. Describe your findings and explain why snow tires are better at providing friction than all-season tires. Can snow tires be left on all year? (4.6) K/U C

Analysis and Application

59. You have two ramps, the first one at a 30° angle with the horizontal and a second one at a 40° angle with the horizontal. You roll a ball from the first ramp, starting at a height of 25 cm, and then let it roll on a horizontal surface for a short distance and then roll up the second ramp. (3.2) K/U T/I
    (a) How high up on the second ramp should the ball roll? Why?
    (b) When the ball rolls back, how high up should it roll on the first ramp?
    (c) Explain why this does not actually happen in the real world. What else is preventing the ball from rolling up to its potential height?

60. A potato gun uses the force of compressed gas to launch pieces of potato with a velocity of 32 m/s on a horizontal plane. If the time it takes the gun to accelerate potatoes to this speed is 0.42 s, and the average potato piece has a mass of 220 g, what is the average force the potato gun exerts on the potatoes? The amount of friction in the tube is negligible. (3.3) T/I

61. An athlete is performing a high-intensity interval training exercise where she jogs for a few minutes and then runs a sprint. The athlete's mass is 71 kg and she jogs at a rate of 3.4 m/s. From a jog, she is able to reach a full sprint of 6.7 m/s in 2.8 s. What is the net force the runner experiences while accelerating to a sprint? (3.3) T/I

62. Two weights, of 9.0 kg and 3.0 kg, are at rest side by side (**Figure 4**). You apply a force of 30.0 N on the first weight for 5.0 s, and they both slide across the floor. The larger weight has a force of friction of 18 N, and the smaller weight has a force of friction of 6.0 N. (3.3, 3.4) T/I C
    (a) Calculate the acceleration of the weights during the first 5.0 s.
    (b) If the applied force is removed, the weights will slow down and stop. Explain why.
    (c) Explain why both weights will move the same distance.

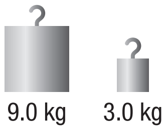


Figure 4

63. Four students are playing tug-of-war. The two students on the right pull with forces of 55 N and 65 N and have masses of 60 kg and 62 kg. The two students on the left pull with forces of 58 N and 70 N, and they have masses of 59 kg and 64 kg. What are the magnitude and direction of the acceleration of the students? (3.3) K/U

64. Nine dogs are pulling a sled in a race. The combined mass of the sled and the driver is 220 kg. (3.3) T/I
    (a) The dogs start from rest and reach a speed of 5.0 km/h in 8.0 s. What is the average force applied by each dog?
    (b) What is the frictional force on the sled if each dog is pulling with a maximum force of 51 N?

65. The force of gravity on Mars is 38 % of the force of gravity on Earth. (3.3) T/I A
    (a) Calculate the acceleration due to gravity on Mars.
    (b) How much would a rover that has a mass of 180 kg weigh, in Newtons, on Mars?
    (c) A rock falls, experiencing a force of gravity of 8500 N on Earth. How much force would it experience on Mars?

66. Several people are on a boat in a lake. Two of them decide to jump off the boat (to the right) at the same time and exert a combined force of 280 N. Their combined mass is 130 kg and the mass of the boat is 220 kg. (3.4) K/U T/I
   (a) Describe the pair of forces the jumpers and the boat exert on each other.
   (b) Determine the magnitude and direction of the acceleration of both the jumpers and the boat.

67. In a turbo jet engine, air is compressed, heated, and then expelled rapidly out the rear of the engine. Use Newton's third law to explain how the engine functions to accelerate the jet. (3.4) K/U C

68. A 2.0 kg mass is tied to a 4.0 kg mass with string B. The 2.0 kg mass is pulled forward with a force of 12 N by string A and both masses accelerate together.
   (a) Find the acceleration and tension in string B if the surface is frictionless.
   (b) Find the acceleration and tension in string B if the coefficient of kinetic friction is 0.10.
   (c) Compare and contrast the results for both (a) and (b). (3.5) K/U T/I C

69. Two toy wagons are tied together by ropes, as shown in **Figure 5**. Rope B is being pulled with a force of 25 N. The mass of wagon 1 is 4.3 kg, and the mass of wagon 2 is 5.5 kg. Assume the force of friction on the wagons is negligible. (3.5) T/I
   (a) What is the acceleration of both of the wagons?
   (b) Calculate the tension in each rope.

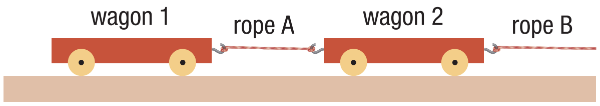


Figure 5

70. Two heavy boxes are at rest as shown in **Figure 6**. (4.1) K/U T/I C
   (a) Find the normal force on box 1 and the normal force on box 2 from the floor.
   (b) Find the normal force on box 1 and the normal force on box 2 from the floor if a person pulls up on box 1 with 55 N.
   (c) Find the normal force on box 1 and the normal force on box 2 from the floor if a person pulls up on box 2 with 55 N.
   (d) Compare and contrast your answers to (b) and (c) and explain why some normal forces changed while others did not.

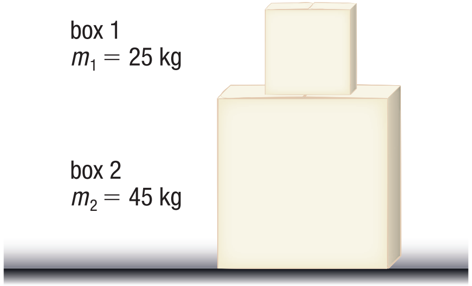


Figure 6

71. A man stacks a small block of wood on top of a larger block and then moves both by pushing the bottom block. The large block has a mass of 25 kg, and the smaller block has a mass of 15 kg. The coefficient of static friction between the two blocks is 0.45. How fast can the man accelerate the blocks without having the smaller block slide off the top? (4.2, 4.3) T/I

72. Some students are testing their knowledge of friction by pushing a block across horizontal surfaces. For the first test, they push a block with 240 N of force across a surface with a coefficient of kinetic friction of 0.4. (4.3) T/I
   (a) The block accelerates at a rate of 0.88 m/s^2. Find the mass of the block.
   (b) The students now slide the block on a new surface while using the same amount of force. The block now moves at constant speed. What is the coefficient of kinetic friction between the block and the new surface?

73. Two teams of students are having a competition to see who can pull two of their own teammates across the gym floor while they sit on a wooden platform. The coefficient of kinetic friction between the platform and the gym floor is 0.30. Team 1 decides to put teammates on the platform with a combined weight of 120 kg so that the rest of their team can pull with a force of 420 N. Team 2 puts two teammates with a combined mass of 130 kg on the platform, and the remaining teammates can pull with a force of 460 N. Calculate the acceleration of each team and determine which team will accelerate the fastest. Assume that the force exerted by each team is enough to overcome the force of static friction. (4.3) T/I

74. In Section 4.3, you learned that static friction does not prevent all motion from objects and, in fact, can be used to create motion. A good example of this is running or walking. Static friction prevents your shoe from slipping on the ground, which enables you to push off and accelerate your body. (4.3) T/I A
    (a) When walking on concrete, the coefficient of static friction between the ground and your shoes is 0.80. How fast can a 72 kg person accelerate on this concrete without slipping?
    (b) If the same person wore the same shoes on ice, where the coefficient of static friction is only 0.075, how fast would she be able to accelerate?

75. Guillaume Amontons was one of the primary scientists that came up with the laws for friction. His second law states that "The force of friction is independent of the apparent area of contact." To help explain this, consider the following scenario: You are trying to slide two wooden blocks across a floor. Both have the same mass and are made of the same material, but one is tall and skinny, giving it a small surface area in contact with the floor, and the other is short and broad, giving it a large surface area in contact with the floor. (4.3) T/I C A
    (a) Which block has a stronger normal force acting on it?
    (b) For the each of the surfaces in contact with the floor, consider only a square centimetre. For this square centimetre, which block has the greater normal force?
    (c) If you know how much frictional force is being applied per unit area, how can you determine the total frictional force?
    (d) Use your answers from (a) through (c) to help explain why the frictional force acting on an object is independent of the surface area in contact.

76. Describe the different factors that tire manufacturers use in the design of their tires to help prevent cars from hydroplaning. (4.4) C

77. In Chapters 3 and 4, you learned about the different ways the physics of forces and friction are applied to create safety devices for cars. In your own words, describe which safety device you think is most necessary for saving lives. How does it work? Is this a relatively new device or an old one, and are there any ways that you can think of for it to be improved? (4.4) T/I C

Evaluation

78. In 2009, the Ontario provincial government made it illegal to use a hand-held cellphone while driving a vehicle. (4.4) T/I C A
    (a) List three reasons why you think the government passed this legislation.
    (b) What effect, if any, do you think this legislation will have on traffic safety?
    (c) Do you believe this legislation is necessary? Explain your reasoning.

79. In Section 4.5, you learned about how forces and friction are applied to different sports. Pick your favourite sport and evaluate the role friction plays. (4.5) T/I C A
    (a) For the main force or action involved, how is friction used? In this case, is more or less friction desired?
    (b) Where is the force of friction the greatest? Where is it the least?
    (c) What measures are taken in either the design of the game or the gear involved to adjust the amount of friction?

80. (a) In Section 4.5, you learned about several different types of bearings that are used to reduce the friction in machines. How do these types of bearings compare with the bearing-like components of your own body? Think of the different ways that your body reduces friction and classify them according to the different types of bearings used.
    (b) Are there any functions or parts of your body that increase friction? What purpose does this serve? How do those parts of your body compare to the materials and technologies you learned about in this unit that also increase friction? (4.5) K/U

81. Use what you have learned in this unit about friction and tires to answer the following questions: (4.6) T/I C A
   (a) Are snow tires worth the cost to a car owner for the safety that they provide? Be sure to take into account the maintenance costs and costs to have the tires changed twice a year.
   (b) Should the government provide incentives or discounts to encourage people to purchase snow tires? If so, how should this work and would it ultimately save money or cost money? Why?

Reflect on Your Learning

82. At the beginning of Chapter 3, you learned two different tools to help solve problems involving forces acting on different objects. Compare the difference between system diagrams and free-body diagrams. Which one do you find more useful for helping you solve problems? Why? Is it possible to solve a problem if only given one or the other? Explain. T/I C

83. The Forces unit contains a lot of information about one of the most fundamental concepts in physics: the use of forces and their impact on how we understand the world. C
   (a) Was there any material, example, or problem that you found particularly interesting or helpful? Were there any moments when you felt as though you gained understanding of real-world situations?
   (b) Do you have a better understanding of the forces behind the everyday events you observe? Have there been any moments where you find yourself explaining the reasoning behind the motion or non-motion of objects you observe?

84. How has your understanding about friction changed? Were there any substances that you thought would have more or less friction compared to others? What did you find most surprising? C

85. Some people might think that the ultimate safe car can be constructed that will always protect the people inside and never cause an accident. Based on what you have learned about forces, do you think this is a reasonable concept? Explain. K/U C A

Research

GO TO NELSON SCIENCE

86. The problems of friction and the need for it to be reduced in machines can be seen even as far back as the sketches of Leonardo da Vinci (**Figure 7**). A few centuries later, Newton came up with his famous laws and began to quantify friction as a force. Only recently, though, have we begun to understand the true causes of friction between the surfaces of objects. Research this topic and write a paragraph describing these causes and how materials scientists use this knowledge to create more efficient ways to reduce friction. K/U C A

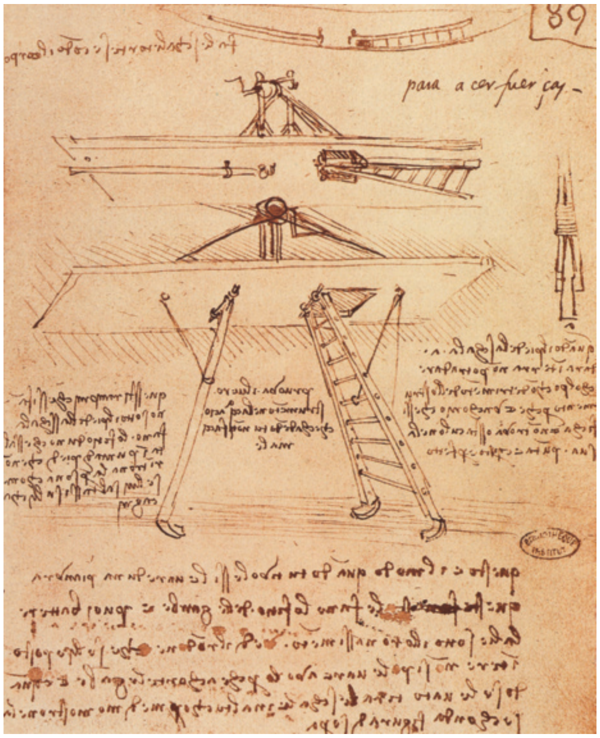


Figure 7

87. As you learned in Chapter 4, when an object moves through any substance, there is a frictional force that increases with the cross-sectional area of the object. This same rule applies whether you are soaring through the air or swimming through the water. The only difference is that the drag coefficient of water is much higher. In the twentieth century, however, scientists discovered a new state of matter called a superfluid. Research this subject and write a few paragraphs on your findings. What makes superfluid so strange? Are there any explanations as to how this state of matter is possible? C A

88. One of the newest types of technology used in car safety are speed–distance sensors that can determine if you are about to have a collision and adjust the car's speed accordingly. Write a few paragraphs about how these sensors work. Have they been found to be accurate in judging distance and preventing collisions, or do they jeopardize a driver's ability to control the car? C A

89. Research the function of a side curtain airbag. Explain how it works, when it is used, and how successful it is in preventing injuries. C A

UNIT 3

Energy and Society

OVERALL EXPECTATIONS

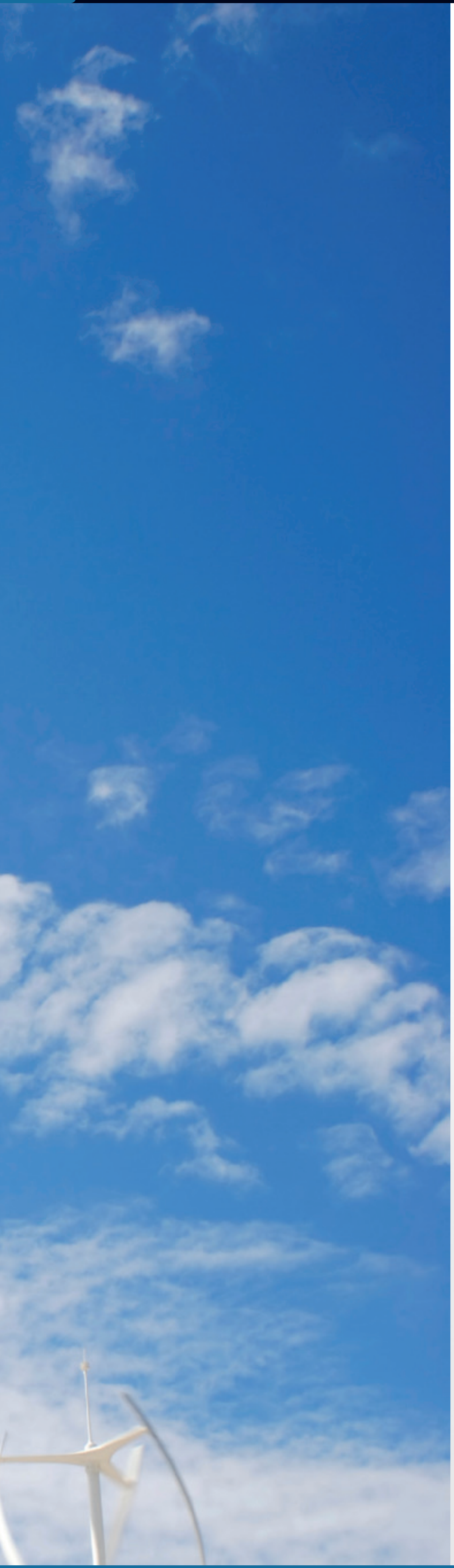
- analyze technologies that apply principles of and concepts related to energy transformations, and assess the technologies' social and environmental impact
- investigate energy transformations and the law of conservation of energy, and solve related problems
- demonstrate an understanding of work, efficiency, power, gravitational potential energy, kinetic energy, nuclear energy, and thermal energy and its transfer (heat)

BIG IDEAS

- Energy can be transformed from one type into another.
- Energy transformation systems often involve thermal energy losses and are never 100 % efficient.
- Although technological applications that involve energy transformations can affect society and the environment in positive ways, they can also have negative effects, and therefore must be used responsibly.

UNIT TASK **PREVIEW**

In this Unit Task, you will be working as part of a Sustainable Energy Commission. You will make recommendations about the use of sustainable energy using your knowledge of energy and society. The Unit Task is described in detail on page 360. As you work through the unit, look for Unit Task Bookmarks to see how information in the section relates to the Unit Task.



GREENING ENERGY USE AND PRODUCTION

Canada is one of the leading producers of energy in the world, and is also one of its biggest users. We use energy for many purposes, including transportation, heating, cooling, industrial production, and leisure. Most of the energy produced in Canada is from coal, crude oil (including gasoline and diesel), natural gas, and radioactive elements such as uranium.

Coal, natural gas, and uranium are extracted from deposits deep within Earth's crust. Crude oil is either mined or purified from oil-soaked tar sands, such as those in northern Alberta. Most of the coal and uranium mined in Canada is used to generate electricity, the most versatile form of energy. However, when coal is used to generate electricity, gases are released into the atmosphere, contributing to climate change.

We are constantly searching for cleaner and "greener" ways of producing electricity. One promising solution is to use wind to produce electricity. Wind turbines provide an environmentally friendlier way of generating electricity. Large groups of turbines, called wind farms, may provide electricity for an entire community. Wind farms may be located on land or in large bodies of water.

Ontario has the largest wind farm in Canada, the Melancthon EcoPower Centre. This wind farm is located in Melancthon Township near Shelburne, Ontario. The Melancthon EcoPower Centre has 133 wind turbines and generates enough electricity to provide for over 52 000 homes. Ontario plans to construct six new wind farms by 2012 that will provide enough electricity for another 150 000 homes. Even more wind farms are planned for the future.

In addition to large wind farms, individual businesses and homeowners may install single wind turbines on their property. These turbines typically produce only enough electricity to run homes, farms, or small businesses. New wind turbine technologies are also addressing some of the problems associated with wind turbines, including excessive noise and danger to flying animals such as birds, bats, and butterflies.

Wind turbines are only one of many exciting technologies being designed to reduce our reliance on coal, oil, natural gas, and uranium. Other alternative energy technologies include solar cells, geothermal systems, tidal turbines, and biofuels. In this unit, you will learn about energy and the technologies being developed to produce and use energy in the most responsible ways possible.

Questions

1. Toronto Hydro is investigating the possibility of building a large wind farm 2 km off the shore of Lake Ontario near Toronto. What social, environmental, and technological factors should Toronto Hydro take into consideration before going ahead with the project?

2. A family has $10 000 this year to spend on non-essentials. It could spend the money on a second car, a family vacation, or other products or activities. Discuss whether the family should use this money to invest in alternative energy technology such as rooftop solar cells or a wind turbine.

UNIT 3 ARE YOU READY?

CONCEPTS

- kinematics and forces
- efficiency
- energy transformations
- thermal energy and heat
- renewable and non-renewable energy resources

SKILLS

- sketching and interpreting free-body diagrams (FBDs)
- researching and collecting information
- planning and conducting investigations
- communicating scientific information clearly and accurately

Concepts Review

1. (a) Calculate the displacement of a motorcycle that accelerates forward from rest to 7.0 m/s in 3.5 s.
   (b) Calculate the magnitude of the net force on a 4.5 kg mass if the mass moves straight up at constant speed. T/I
2. Identify the forms of energy depicted in **Figure 1**. K/U

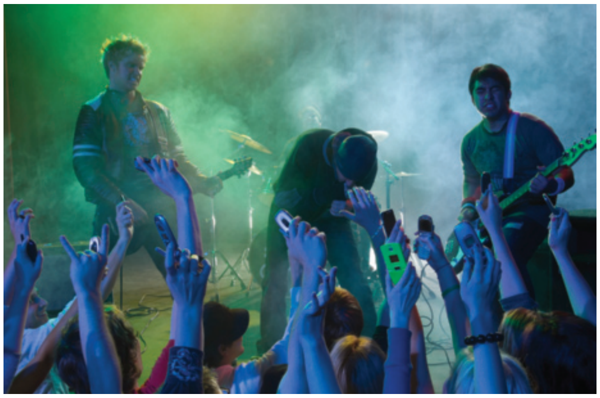


Figure 1

3. Describe two energy changes occurring in **Figure 2** and two energy changes occurring in **Figure 3** (e.g., in Figure 2, the television changes electrical energy into light energy, sound energy, and thermal energy). K/U C

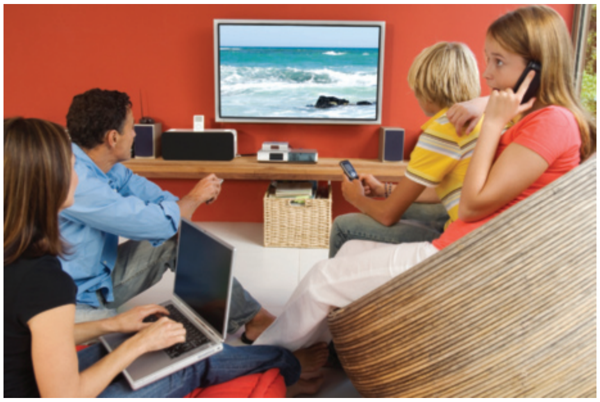


Figure 2

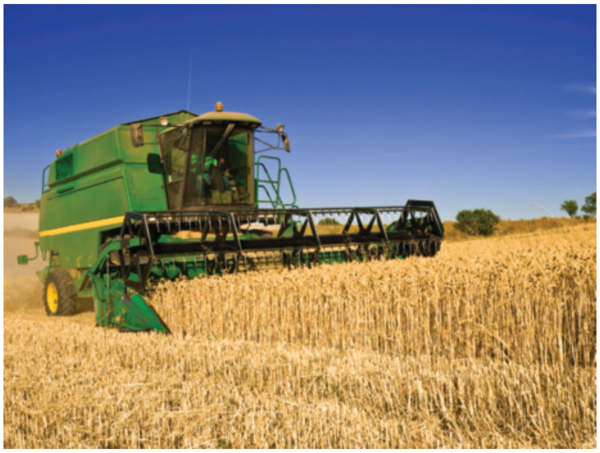


Figure 3

4. (a) **Table 1** contains values involved in the calculation of the efficiency of various devices. Copy Table 1 into your notebook and fill in the missing values.

Table 1

Device	Electric lawnmower	Incandescent light bulb
input energy (J)	1650	80
output energy (J)	250	
efficiency (%)		5

   (b) Account for the difference between the input energy and the output energy for the electric lawnmower in Table 1. K/U T/I
5. (a) What is the difference between thermal energy and heat?
   (b) What is the relationship between the temperature of a drop of water and the kinetic energy of the water molecules in the drop of water? K/U

6. (a) You have used the particle theory of matter to describe the three states of matter. Copy **Table 2** into your notebook and complete it using the particle theory of matter.

Table 2

State	Relative distance between particles	Motion of particles	Diagram of state of matter
solid			
liquid			
gas			

   (b) Explain why both liquids and gases take the shape of their containers, but solids do not.
   (c) What happens to the particles in a substance when you heat it up and it starts to change state? K/U C

7. (a) Explain the difference between a thermal insulator and a thermal conductor.
   (b) Give one example of a good thermal insulator and one example of a good thermal conductor.
   (c) Should a well-constructed window be made primarily from insulators or conductors? Explain your reasoning.
   (d) Give one example of a simple everyday utensil or device that must be constructed out of
      (i) only thermal conductors
      (ii) only thermal insulators
      (iii) both thermal insulators and thermal conductors K/U C

8. Describe two advantages and two disadvantages of each of the following systems for generating electrical energy. K/U
   (a) hydroelectric power plant
   (b) nuclear power plant

9. (a) Draw a simple diagram of an atom. Label the nucleus, protons, neutrons, and electrons.
   (b) How do atoms and ions differ?
   (c) How do atoms of different elements differ? K/U C

10. Examine a periodic table (see Appendix B at the back of this book). The table is divided into rows and columns. K/U
   (a) What happens to the number of electrons as you move from one element to the next in the same row?
   (b) What tends to happen to the number of protons as you move from one element to the next in the same row?

Skills Review

11. A boy pulls a sleigh along a flat, snow-covered sidewalk by tugging on a rope that makes a 45° angle with the ground. K/U T/I C
   (a) Sketch a free-body diagram of this situation if the boy pulls on the rope with a force of 7.0 N and there is a force of friction of 3.0 N opposing the sleigh's motion (the sleigh has a mass of 17 kg).
   (b) Explain what you think will happen to the speed of the sleigh if the boy pulls it for
      (i) 20 m
      (ii) 60 m
   (c) What effect does the displacement have on the final velocity for a mass under the influence of a constant net force?

12. In an investigation, a student takes a 50 g ice cube from the freezer at a temperature of –6 °C and puts it in a cup of water at 70 °C. The mass of liquid water present is 50 g. The goal is to determine the final temperature of the water in the cup, assuming there is no loss of energy to the surroundings. K/U T/I
   (a) What other equipment would you need to perform this experiment?
   (b) Make a prediction for the final temperature of the water. Explain your reasoning.
   (c) What are some possible sources of error in this experiment?
   (d) Describe a way to reduce the error in this experiment.

CAREER PATHWAYS **PREVIEW**

Throughout this unit you will see Career Links in the margins. These links mention careers that are relevant to Energy and Society. On the Chapter Summary page at the end of each chapter you will find a Career Pathways feature that shows you the educational requirements of the careers. There are also some career-related questions for you to research.

CHAPTER

5 Work, Energy, Power, and Society

KEY CONCEPTS

After completing this chapter you will be able to

- describe and define qualitatively and quantitatively the scientific concepts of work, energy, power, and the law of conservation of energy
- solve problems involving work, energy, power, and the law of conservation of energy
- distinguish qualitatively and quantitatively between kinetic energy and potential energy, especially gravitational potential energy
- describe various forms of energy and their common uses
- distinguish between renewable and non-renewable energy resources
- design and conduct investigations involving work, energy, and energy transformations
- make research-informed decisions about the wise use of energy in everyday life

What Are Work, Energy, and Power, and How Do They Affect Society and the Environment?

Snowboarding is a popular winter sport. When Shaun White won the gold medal in the men's snowboarding half-pipe competition at the Vancouver 2010 Winter Olympics, he scaled 7.6 m high walls of snow, sometimes jumping 9 m above the top edge—a total height of over 16 m above the ground (the equivalent of a five-storey building)!

In the Olympic half-pipe competition, snowboarders slide down a 120 m long half-cylinder-shaped course (the half-pipe) in a crisscross fashion, soaring over the top edges on each cross. While in the air, they perform amazing somersaults and twists. Competitors are judged on the height of their jumps (getting air), the difficulty of their twists and flips, the steadiness of their landings, and their overall form.

Snowboarders alternately speed up and slow down as they crisscross the half-pipe. They speed up when they slide down one side and slow down when they climb the other side and soar into the air. The faster they descend on one side, the higher they will be able to leap into the air on the other side. Higher jumps allow the athletes to perform more spectacular acrobatics. Snowboarders do everything they can to increase their speed on their descents.

Half-pipe snowboarders have to be very fit. They need to have strong muscles and a good sense of balance to perform the flips and twists that judges and the public expect to see. In this chapter, you will explore some of the physics ideas that help us understand the ups and downs of half-pipe snowboarding. These same ideas help us explain how roller coasters work, how waterfalls can be used to generate electricity, and why it is wiser to use compact fluorescent lamps than incandescent light bulbs.

STARTING **POINTS**

Answer the following questions using your current knowledge. You will have a chance to revisit these questions later, applying concepts and skills from the chapter.

1. What is a force?
2. Provide an example of an energy transformation.
3. Why are fossil fuels non-renewable energy resources?
4. Which of the following uses more energy in 1 h of use: a 100 W light bulb or a 50 W light bulb? Explain.

Mini Investigation

Pizza Pan Half-Pipe

Skills: Predicting, Performing, Observing, Analyzing, Evaluating, Communicating

SKILLS HANDBOOK A2.1

In this activity, you will use a marble to model the motion of a half-pipe snowboarder.

Equipment and Materials: 3–4 textbooks; small marble; metric ruler; large sheet of paper; circular pizza pan (30 cm diameter) with edge; tape

1. Stack 3–4 textbooks in a step-like fashion on a tabletop so that part of the edge of each book is exposed.
2. Carefully cut a sheet of paper so that it fits inside the bottom of a circular pizza pan.
3. Tape the paper into the bottom of the pan and place pencil marks at the 4 o'clock and 6 o'clock positions.
4. Lean the top edge of the pan on the lowest book in the stack. Tape the bottom edge of the pan at the 6 o'clock position onto the tabletop so that it does not move.
5. Place a marble on the inside edge of the pan at the level of the 4 o'clock pencil mark (this is the marble's initial position). Release the marble and let it roll along the inside edge of the pan. Repeat this 2 or 3 times, noting the height to which the marble rises on the other side. Place a pencil mark at that point (this is the marble's final position).
6. Use a ruler to measure the vertical distance from the tabletop to the marble's initial and final positions.
7. Remove the tape from the lower edge of the pan and increase its slope by leaning the top edge against a higher book. Tape the bottom of the pan to the table at the 6 o'clock position.
8. Repeat Steps 5 and 6, releasing the marble from the same initial position.
9. Explore the motion of the marble further by repeating Steps 7 and 8 a few more times.

A. Describe any differences in the initial and final positions of the marble in each case. T/I C

B. Compare the results you obtained in Steps 5, 6, 8, and 9, and try to provide reasons for any observed differences. T/I

5.1 Work

Figure 1 Olympic weightlifter Marilou Dozois-Prevost did work on a barbell while lifting it over her head.

It took a lot of work for Canadian Olympic weightlifter Marilou Dozois-Prevost to lift a 76 kg barbell over her head at the 2008 Beijing Olympics (**Figure 1**). In weightlifting, you do work by moving weights from the ground to a position above your head. To lift the weights, you apply an upward force that displaces (moves) the weights in the direction of the force. This form of work is called mechanical work. In science, **mechanical work** is done on an object when a force displaces the object in the direction of the force or a component of the force.

mechanical work (W) applying a force on an object that displaces the object in the direction of the force or a component of the force

Work Done by a Constant Force

Mathematically, the mechanical work, W, done by a force on an object is the product of the magnitude of the force, F, and the magnitude of the displacement of the object, Δd:

$$W = F\Delta d$$

This equation applies only to cases where the magnitude of the force is constant and where the force and the displacement are in the same direction. Since work is a product of the magnitude of the force and the magnitude of the displacement, the symbols for force and displacement in the equation $W = F\Delta d$ are written without the usual vector notations $(\vec{F}, \Delta\vec{d})$. Work is a scalar quantity; there is no direction associated with work.

The SI unit for work is the newton metre (N·m). The newton metre is called the joule (J) in honour of James Prescott Joule, an English physicist who investigated work, energy, and heat (1 N·m = 1 J). Notice that we do not consider the amount of time the force acts on an object or the velocities or accelerations of the object in the calculation of work.

LEARNING **TIP**

Describing Work
When describing work, you should always mention the object that does the work and the object that the work is done on.

Work Done When Force and Displacement Are in the Same Direction

The equation $W = F\Delta d$ may be used to calculate the amount of mechanical work done on an object when force and displacement are in the same direction. In the following Tutorial, you will solve two Sample Problems involving mechanical work in which a force displaces an object in the same direction as the force.

Tutorial 1 Using the Equation $W = F\Delta d$ to Calculate Work Done

In this Tutorial, you will use the equation $W = F\Delta d$ to calculate the amount of work done by a force when the force and displacement are in the same direction.

Sample Problem 1

How much mechanical work does a store manager do on a grocery cart if she applies a force with a magnitude of 25 N in the forward direction and displaces the cart 3.5 m in the same direction (**Figure 2**)?

We are given the force, F_a, and the cart's displacement, Δd. Since the force and displacement are in the same direction, we may use the equation $W = F_a\Delta d$ to solve the problem.

Given: $F_a = 25$ N; $\Delta d = 3.5$ m

Required: W

Analysis: $W = F_a\Delta d$

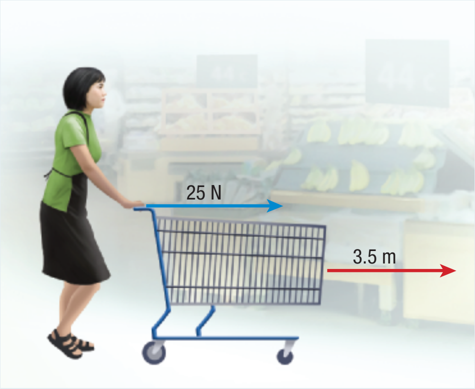


Figure 2

Solution: $W = F_a \Delta d$

$$= (25\text{ N})(3.5\text{ m})$$

$$= 88\text{ N}\cdot\text{m}$$

$$W = 88\text{ J}$$

Statement: The store manager does 88 J of mechanical work on the grocery cart.

Sample Problem 2

A curler applies a force of 15.0 N on a curling stone and accelerates the stone from rest to a speed of 8.00 m/s in 3.50 s. Assuming that the ice surface is level and frictionless, how much mechanical work does the curler do on the stone?

In this problem, we are given the force but not the stone's displacement. However, in Chapter 1, you learned that the displacement of an accelerating object may be determined using the equation $\Delta d = \left(\frac{v_1 + v_2}{2}\right)\Delta t$ if you know the initial speed, v_1, the final speed, v_2, and the time interval, Δt, in which the object's change in speed occurs.

Given: $F_a = 15.0\text{ N}$; $v_1 = 0\text{ m/s}$; $v_2 = 8.00\text{ m/s}$; $\Delta t = 3.50\text{ s}$

Required: W

Analysis: $\Delta d = \left(\frac{v_1 + v_2}{2}\right)\Delta t$; $W = F_a \Delta d$

Solution: First, we calculate Δd using the v_1, v_2, and Δt values given.

$$\Delta d = \left(\frac{v_1 + v_2}{2}\right)\Delta t$$

$$= \left(\frac{0 + 8.00\text{ m/}\cancel{\text{s}}}{2}\right)(3.50\text{ }\cancel{\text{s}})$$

$$\Delta d = 14.0\text{ m}$$

We now substitute the values of F_a and Δd into the equation for work and solve.

$$W = F_a \Delta d$$

$$= (15.0\text{ N})(14.0\text{ m})$$

$$= 2.10 \times 10^2\text{ N}\cdot\text{m}$$

$$W = 2.10 \times 10^2\text{ J}$$

Statement: The curler does 2.10×10^2 J of mechanical work on the curling stone.

Practice

1. A 0.50 kg laboratory dynamics cart with an initial velocity of 3.0 m/s [right] accelerates for 2.0 s at 1.2 m/s^2 [right] when pulled by a string. Assume there is no friction acting on the cart. T/I
   (a) Calculate the force exerted by the string on the cart. [ans: 0.60 N]
   (b) Calculate the displacement of the cart. [ans: 8.4 m]
   (c) Calculate the mechanical work done by the string on the cart. [ans: 5.0 J]

Work Done When Force and Displacement Are in Different Directions

In some cases, an object may experience a force in one direction while the object moves in a different direction. For example, this occurs when a person pulls on a suitcase with wheels and a handle (**Figure 3(a)**). The free-body diagram (FBD) for this situation is shown in **Figure 3(b)**. In this case, the applied force is directed toward the person's hips, while the suitcase rolls on the floor in the forward direction. The FBD shows all the forces acting on the suitcase, including the force of gravity (F_g), the normal force (F_N), and the applied force resolved into horizontal (F_h) and vertical (F_v) components.

LEARNING **TIP**

Work

Work has a different meaning in science than it does in everyday life. In science, work is done only when a force displaces an object. If a force is applied on an object, but the object does not move, then no work is done. For example, Marilou Dozois-Prevost was applying a force on the barbell while she was lifting it and while she was holding it motionless over her head. However, she did work on the barbell (in the scientific sense) only while she was lifting it, not while holding it over her head as in Figure 1.

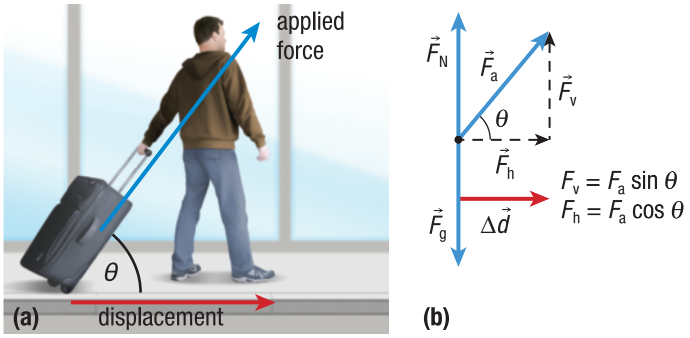


Figure 3 (a) A system diagram of a trolley suitcase displaced to the right (b) FBD of a trolley suitcase displaced to the right

(We will assume that the force of friction is negligible.) The FBD also indicates that the applied force vector, $\vec{F}_a$, makes an angle θ with the displacement vector, $\Delta\vec{d}$.

The magnitude of F_h is given by the equation

$$F_h = F_a \cos \theta$$

Since the horizontal component, F_h, is the only force in the direction of the suitcase's displacement, it is the only force that causes the suitcase to move along the floor. Thus, the amount of mechanical work done by F_h on the suitcase may be calculated using the equation $W = F_a(\cos \theta)\Delta d$ or, in general,

$$\boxed{W = F(\cos \theta)\Delta d}$$

where W is the work done, F is the force, and $\cos \theta$ is the angle between the force and the displacement vector, Δd.

What about the vertical component of F_a? F_v does no work on the suitcase because the suitcase is not displaced in the direction of F_v. Since F_v is perpendicular to the suitcase's displacement along the floor ($\theta = 90°$), F_v does no work on the suitcase. This can be calculated using the work equation, $W = F_a(\cos \theta)\Delta d$, where $\theta = 90°$:

$$\begin{aligned} W &= F_a(\cos \theta)\Delta d \\ &= F_a(\cos 90°)\Delta d \\ &= F_a(0)\Delta d, \text{ since } \cos 90° = 0 \\ W &= 0\ \text{J} \end{aligned}$$

This result illustrates an important principle of mechanical work. In general, the work done by a force is zero when the force's direction is perpendicular to the object's displacement; that is, when $\theta = 90°$, $\cos 90° = 0$, and $W = 0$ J.

LEARNING TIP

Dot Products
The scalar product of two vectors is commonly indicated by placing a dot between the vector symbols (e.g., $W = \vec{F} \cdot \Delta\vec{d}$) and unit symbols (N·m). It is for this reason that a scalar product is sometimes called a dot product. A dot product may also be represented by using scalar symbols without the dot between them (as we do in this book), $W = F\Delta d$.

Tutorial 2 Using the Equation $W = F(\cos \theta)\Delta d$ to Calculate Work Done

In this Tutorial, you will analyze two cases in which objects experience a force in one direction and a displacement in a different direction.

CASE 1: AN OBJECT IS DISPLACED BY A FORCE THAT HAS A COMPONENT IN THE DIRECTION OF THE DISPLACEMENT

Sample Problem 1

Calculate the mechanical work done by a custodian on a vacuum cleaner if the custodian exerts an applied force of 50.0 N on the vacuum hose and the hose makes a 30.0° angle with the floor. The vacuum cleaner moves 3.00 m to the right on a level, flat surface. The system diagram for this problem is shown in **Figure 4**.

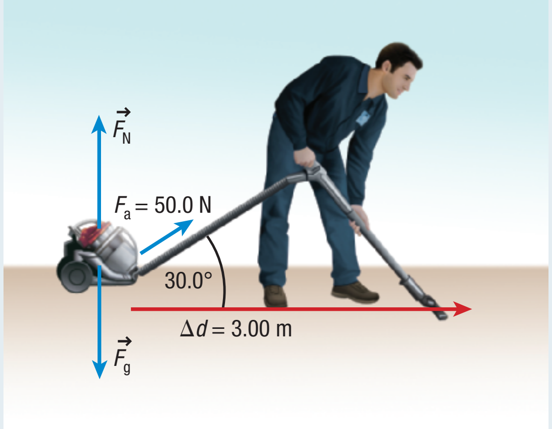


Figure 4

In this problem, the system diagram shows that three forces are acting on the vacuum cleaner: the force of gravity, $\vec{F}_g$; the normal force, $\vec{F}_N$; and the applied force, $\vec{F}_a$. Only the magnitude of the component of $\vec{F}_a$ in the direction of the displacement ($F_a \cos \theta$) does work on the vacuum cleaner. The other two forces ($\vec{F}_N$ and $\vec{F}_g$) do no work on the vacuum cleaner because they are perpendicular to the displacement.

Given: $F_a = 50.0$ N; $\Delta d = 3.00$ m; $\theta = 30.0°$

Required: W

Analysis: $W = F_a(\cos \theta)\Delta d$

Solution:
$$\begin{aligned} W &= F_a(\cos \theta)\Delta d \\ &= (50.0\ \text{N})(\cos 30.0°)(3.00\ \text{m}) \\ &= 1.30 \times 10^2\ \text{N·m} \\ W &= 1.30 \times 10^2\ \text{J} \end{aligned}$$

Statement: The custodian does 1.30×10^2 J of mechanical work on the vacuum cleaner.

CASE 2: AN OBJECT IS DISPLACED, BUT THERE IS NO FORCE OR COMPONENT OF A FORCE IN THE DIRECTION OF THE DISPLACEMENT

Sample Problem 2

Ranbir wears his backpack as he walks forward in a straight hallway. He walks at a constant velocity of 0.8 m/s for a distance of 12 m. How much mechanical work does Ranbir do on his backpack?

Consider the system diagram shown in **Figure 5**. Ranbir walks at constant velocity. Thus, there is no acceleration in the direction of displacement and no applied force on the backpack in that direction. The only applied force on the backpack is the force that Ranbir's shoulders apply on the backpack ($\vec{F}_a$) to oppose the force of gravity on the backpack ($\vec{F}_g$, the backpack's weight). However, neither the applied force nor the force of gravity does work on the backpack because both forces are perpendicular to the displacement. Therefore, Ranbir does no mechanical work at all on the backpack.

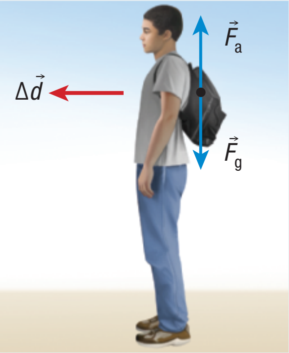


Figure 5

Practice

1. A person cutting a flat lawn pushes a lawnmower with a force of 125 N at an angle of 40.0° below the horizontal for 12.0 m. Determine the mechanical work done by the person on the lawnmower. T/I [ans: 1.15 kJ]
2. A father pulls a child on a toboggan along a flat surface with a rope angled at 35.0° above the horizontal. The total mechanical work done by the father over a horizontal displacement of 50.0 m is 2410 J. Determine the work done on the toboggan by the normal force and the force of gravity, and explain your reasoning. T/I [ans: 0]

Work Done When a Force Fails to Displace an Object

In some cases, a force is applied on an object, but the object does not move: no displacement occurs. For example, when you stand on a solid floor, your body applies a force on the floor equal to your weight ($\vec{F}_a = \vec{F}_g$), but the floor does not move. Your body does no work on the floor because the floor is not displaced. In the following Tutorial, you will examine a situation in which a force is applied but no displacement occurs.

Tutorial 3 Applied Force Causing No Displacement

In the following Sample Problem, you will determine how much work is done when an applied force does not cause displacement.

Sample Problem 1

How much mechanical work is done on a stationary car if a student pushing with a 300 N force fails to displace the car?

Given: $F_a = 300$ N; $\Delta d = 0$ m

Required: W

Analysis: $W = F\Delta d$

Solution: $W = F\Delta d$

$= (300 \text{ N})(0 \text{ m})$

$W = 0$ J

Statement: No mechanical work is done by the student on the car.

In general, if a force fails to displace an object, then the force does no work on the object. Another case in which no work is done occurs when an object moves on a frictionless surface at constant velocity with no horizontal forces acting on it. For example, an air hockey puck that travels 2 m at constant velocity on an air hockey table experiences a displacement but no force (assuming no friction). In this case,

$$\begin{aligned} F_a &= 0\text{ N and } \Delta d = 2\text{ m} \\ W &= F_a\Delta d \\ &= (0\text{ N})(2\text{ m}) \\ W &= 0\text{ J} \end{aligned}$$

No work is done on the puck as it glides at constant velocity on the air hockey table.

Practice

1. There is no work done for each of the following examples. Explain why. K/U C
   - (a) A student leans against a brick wall of a large building.
   - (b) A space probe coasts at constant velocity toward a planet.
   - (c) A textbook is sitting on a shelf.

Positive and Negative Work

In many cases, an object experiences several forces at the same time. For example, when Marilou Dozois-Prevost lifted weights at the Beijing Olympics, she applied a force, $\vec{F}_a$, on the barbell in the upward direction, while Earth applied a force of gravity, $\vec{F}_g$, on the barbell in the opposite direction (**Figure 6**).

In cases such as this, the total work done on the object is equal to the algebraic sum of the work done by all of the forces acting on the object. We assume that the forces act in the same direction as the object's displacement or in a direction opposite the object's displacement ($\theta = 0°$ or $\theta = 180°$). In the following Tutorial, you will calculate the total work done on an object when the object experiences forces in opposite directions.

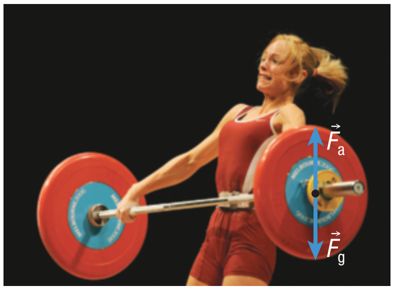


Figure 6 Marilou Dozois-Prevost applied a force on the barbell in the upward direction, while Earth applied a force of gravity in the downward direction.

Tutorial 4 Positive and Negative Work

In the following Sample Problem, we will consider the total work done on an object when the object experiences two forces: an applied force in the same direction as its displacement and another force (a force of friction) in the opposite direction.

Sample Problem 1

A shopper pushes a shopping cart on a horizontal surface with a horizontal applied force of 41.0 N for 11.0 m. The cart experiences a force of friction of 35.0 N. Calculate the total mechanical work done on the shopping cart.

In this problem, the applied force, $\vec{F}_a$, does work, W_a, on the cart, and the force of friction, $\vec{F}_f$, does work, W_f, on the cart. While $\vec{F}_a$ acts in the same direction as the cart's displacement, $\vec{F}_f$ acts in the opposite direction. Thus, we will use the equation $W = F(\cos\theta)\Delta d$ to calculate work. We will solve this problem in three parts.

(a) Calculate the work done by the applied force using the equation $W_a = F_a(\cos\theta)\Delta d$.

(b) Calculate the work done by the force of friction using the equation $W_f = F_f(\cos\theta)\Delta d$.

(c) Determine the total, or net, work done on the cart, W_{net}, by calculating the sum of W_a and W_f.

Given: $F_a = 41.0$ N; $\Delta d = 11.0$ m; $F_f = 35.0$ N

Required: W_a; W_f; W_{net}

(a) mechanical work done by the applied force on the cart

Analysis: $W_a = F_a(\cos\theta)\Delta d$

Solution: Since the force of friction acts in the same direction as the displacement, $\theta = 0°$ here.

$$\begin{aligned} W_a &= F_a(\cos\theta)\Delta d \\ &= (41.0\text{ N})(\cos 0°)(11.0\text{ m}) \\ &= 451\text{ N}\cdot\text{m} \\ W_a &= 451\text{ J} \end{aligned}$$

Statement: The applied force does 451 J of mechanical work on the cart.

(b) mechanical work done by the force of friction on the cart

Analysis: $W_f = F_f(\cos\theta)\Delta d$

Solution: Since the force of friction acts in the opposite direction of the displacement, $\theta = 180°$ here.

$$\begin{aligned} W_f &= F_f(\cos\theta)\Delta d \\ &= (35.0\text{ N})(\cos 180°)(11.0\text{ m}) \\ W_f &= -385\text{ J} \end{aligned}$$

Statement: The force of friction does −385 J of mechanical work on the cart.

(c) net work done by the applied force and the force of friction on the cart

Solution: $W_{net} = W_a + W_f$

$$\begin{aligned} W_{net} &= W_a + W_f \\ &= 451\text{ J} + (-385\text{ J}) \\ W_{net} &= 66\text{ J} \end{aligned}$$

Statement: The net work done by the applied force and the force of friction on the cart is 66 J.

Practice

1. Curtis pushes a bowl of cereal along a level counter a distance of 1.3 m. What is the net work done on the bowl if Curtis pushes the bowl with a force of 4.5 N and the force of friction on the bowl is 2.8 N? T/I [ans: 2.2 J]
2. A crane lifts a 450 kg beam 12 m straight up at a constant velocity. Calculate the mechanical work done by the crane. T/I [ans: 53 kJ]

Graphing Work Done

The work done by a force on an object may be represented graphically by plotting the magnitude of the force, *F*, on the *y*-axis and the magnitude of the object's position, *d*, on the *x*-axis. In such cases, we assume that the force acts in the same direction as the object's displacement or in a direction opposite the object's displacement ($\theta = 0°$ or $\theta = 180°$). This is known as a force–position, or *F–d*, graph. **Figure 7** shows an *F–d* graph for a constant force acting through a displacement Δd. The work done, *W*, is equal to the area under the *F–d* graph (the shaded rectangle) and is equal in value to the product $F\Delta d$.

Positive and negative work may also be represented using an *F–d* graph. In **Figure 8**, positive work (work done when force and displacement are in the same direction) is represented by the blue rectangle above the *d*-axis. Negative work (work done when force and displacement are in opposite directions) is represented by the red rectangle below the *d*-axis.

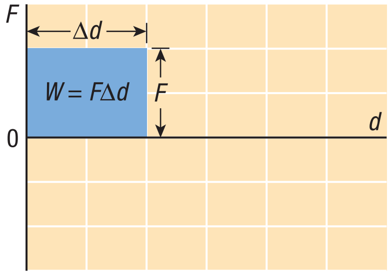


Figure 7 *F–d* graph for a constant force acting through a displacement

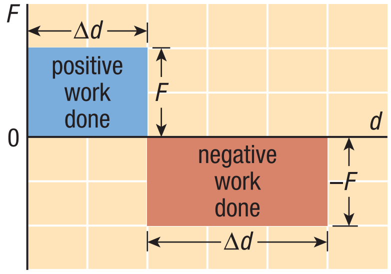


Figure 8 *F–d* graph representing positive and negative work done

Work Done by a Changing Force

The equation $W = F\Delta d$ or $W = F(\cos\theta)\Delta d$ can be used only to calculate the mechanical work done on an object when the force on the object is constant. However, in many cases, a force varies in magnitude during a displacement. For example, when a bus driver steadily depresses the accelerator pedal of a bus, the force the engine applied on the wheels increases uniformly. The force is not constant.

The work done on an object by a changing force that is in the same direction as the object's displacement may be represented using an *F–d* graph. **Figure 9** shows an *F–d* graph for a uniformly increasing force. As in the case of a constant force, the work done is equal to the area under the *F–d* graph. In this case, the work done, *W*, is equal in value to the product $F_{av}\Delta d$. F_{av} represents the average force applied to the object as it is displaced.

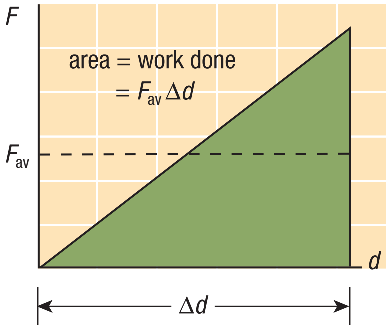


Figure 9 *F–d* graph representing a uniformly increasing force

Mini Investigation

Human Work

Skills: Predicting, Performing, Observing, Analyzing SKILLS HANDBOOK A2.1

In this activity, you will determine the work done by a person lifting a book and a shoe.

Equipment and Materials: scale; textbook; tape measure or metre stick; desk; shoe

1. Use a scale to measure the mass of a textbook. Calculate the textbook's weight in newtons.
2. Use a tape measure or metre stick to measure the vertical distance from the floor to the top of a desk.
3. Place the textbook on the floor beside the desk and lift it straight up to the top of the desk at a constant speed.
4. Calculate the work you did on the book.
5. Obtain a clean shoe. Hold the shoe in your hand for a few seconds to get a feel for its weight.
6. Predict the amount of work you would have to do on the shoe to lift the shoe straight up from the floor to the top of the desk at constant speed.
7. Test your prediction by determining the weight of the shoe and then lifting the shoe from the floor to the top of the desk and calculating the work done.

A. Compare the amount of work you did on the textbook to the amount of work you did on the shoe. T/I

B. Evaluate the prediction you made in Step 6 on the basis of the results you obtained in Step 7. T/I

C. Calculate the height above the floor to which you would have to lift the shoe to do the same amount of work as you did on the textbook. T/I

5.1 Summary

- Mechanical work is done when a force displaces an object in the direction of the force or a component of the force.
- The equation $W = F(\cos\theta)\Delta d$ may be used to calculate the amount of mechanical work done on an object.
  - If the force on an object and the object's displacement are in the same direction, then $\theta = 0°$, $\cos\theta = 1$, the equation $W = F(\cos\theta)\Delta d$ becomes $W = F\Delta d$, and the amount of work is a positive value.
  - If the force on an object and the object's displacement are perpendicular, then $\theta = 90°$, $\cos\theta = 0$, and $W = 0$ J (no work is done).
  - If a force acts on an object in a direction opposite the object's displacement, then $\theta = 180°$, $\cos\theta = -1$, the equation $W = F(\cos\theta)\Delta d$ becomes $W = (F\Delta d)(-1)$, and the amount of work is a negative value.
- When the force on an object and the displacement of the object are parallel (in the same direction or opposite in direction), the work done on the object may be determined from an F–d graph by finding the area between the graph and the position axis. The work is positive if the area is above the position axis and negative if it is below the position axis.
- When a force varies in magnitude during a displacement, the work done is equal to the product of the average force, F_{av}, and the displacement, Δd.

5.1 Questions

1. A 25.0 N applied force acts on a cart in the direction of the motion. The cart moves 13.0 m. How much work is done by the applied force? T/I
2. A tow truck pulls a car from rest onto a level road. The tow truck exerts a horizontal force of 1500 N on the car. The frictional force on the car is 810 N. Calculate the work done by each of the following forces on the car as the car moves forward 12 m: T/I
   - (a) the force of the tow truck on the car
   - (b) the force of friction
   - (c) the normal force
   - (d) the force of gravity
3. A child pulls a wagon by the handle along a flat sidewalk. She exerts a force of 80.0 N at an angle of 30.0° above the horizontal while she moves the wagon 12 m forward. The force of friction on the wagon is 34 N. T/I
   - (a) Calculate the mechanical work done by the child on the wagon.
   - (b) Calculate the total work done on the wagon.
4. A horizontal rope is used to pull a box forward across a rough floor doing 250 J of work over a horizontal displacement of 12 m at a constant velocity. T/I C
   - (a) Draw an FBD of the box.
   - (b) Calculate the tension in the rope.
   - (c) Calculate the force of friction and the work done by the force of friction. Explain your reasoning.
5. A 62 kg person in an elevator is moving up at a constant speed of 4.0 m/s for 5.0 s. T/I C
   - (a) Draw an FBD of the person in the elevator.
   - (b) Calculate the work done by the normal force on the person.
   - (c) Calculate the work done by the force of gravity on the person.
   - (d) How would your answers change if the elevator were moving down at 4.0 m/s for 5.0 s?
6. A force sensor pulls a cart horizontally from rest. The position of the cart is recorded by a motion sensor. The data were plotted on a graph as shown in **Figure 10**. The applied force and the displacement are parallel. What is the work done on the cart by the force sensor after a displacement of 0.5 m? T/I

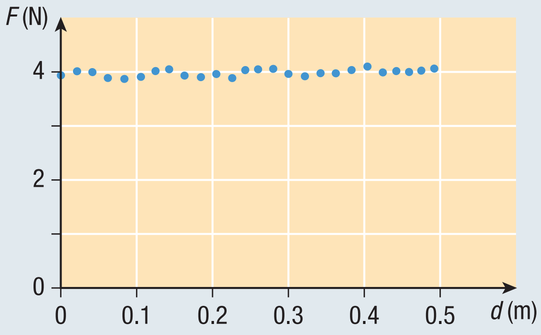


Figure 10

7. A rope pulls a 2.0 kg bucket straight up, accelerating it from rest at 2.2 m/s^2 for 3.0 s. T/I
   - (a) Calculate the displacement of the bucket.
   - (b) Calculate the work done by each force acting on the bucket.
   - (c) Calculate the total mechanical work done on the bucket.
   - (d) Calculate the net force acting on the bucket and the work done by the net force. Compare your answer to the total mechanical work done on the bucket as calculated in (c).
8. In your own words, explain if mechanical work is done in each of the following cases: K/U C
   - (a) A heavy box sits on a rough horizontal counter in a factory.
   - (b) An employee pulls on the box with a horizontal force and nothing happens.
   - (c) The same employee goes behind the box and pushes even harder, and the box begins to move. After a few seconds, the box slides onto frictionless rollers and the employee lets go, allowing the box to move with a constant velocity.
9. The graph in **Figure 11** shows the force acting on a cart from a spring. The force from the spring is either in the same direction as the cart's displacement or in the opposite direction. T/I C

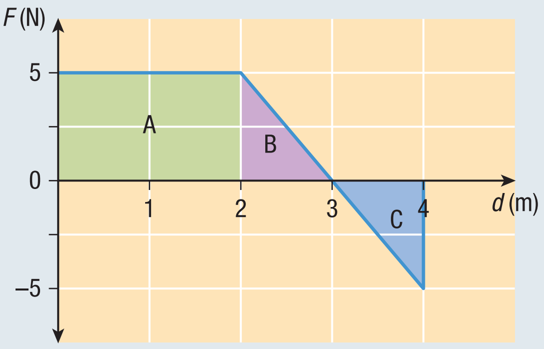


Figure 11

   - (a) Calculate the work done in sections A, B, and C.
   - (b) Calculate the total work done.
   - (c) Explain why the work done in section C must be negative.
10. Describe two ways to determine the total work done by one object on another object. K/U C
11. Consider the equation $W = F(\cos\theta)\Delta d$. K/U C
   - (a) Using the equation, explain why a force perpendicular to the displacement does zero work.
   - (b) Using the equation, explain why a force opposite to the displacement does negative work.

5.2

Energy

energy the capacity to do work

As you learned in Section 5.1, mechanical work is done by applying forces on objects and displacing them. How are people, machines, and Earth able to do mechanical work? The answer is energy: **energy** provides the ability to do work. Objects may possess energy whether they are moving or at rest. In this section, we will focus on a form of energy possessed only by moving objects.

Kinetic Energy: The Energy of Moving Objects

kinetic energy (E_k) energy possessed by moving objects

A moving object has the ability to do work because it can apply a force to another object and displace it. The energy possessed by moving objects is called **kinetic energy (E_k)** (from the Greek word kinema, meaning "motion"). For example, a moving hammer has kinetic energy because it has the ability to apply a force on a nail and push the nail into a piece of wood (**Figure 1**). The faster the hammer moves, the greater its kinetic energy, and the greater the displacement of the nail. In general, objects with kinetic energy can do work on other objects.

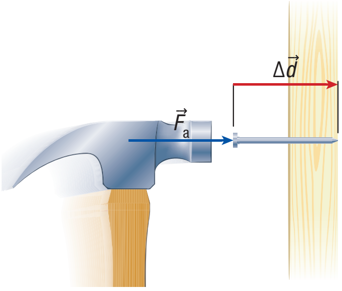


Figure 1 A moving hammer can do work on a nail because it has kinetic energy.

Quantifying Kinetic Energy

Since kinetic energy is energy possessed by moving objects, consider a motorcycle moving in a straight line on a roadway (**Figure 2**). The motorcyclist and the motorcycle have a total mass, m. When the motorcyclist twists the motorcycle's throttle, the motorcycle experiences a net force of magnitude, F_{net}, that accelerates the motorcycle from an initial speed, v_i, to a final speed, v_f. The acceleration occurs over a displacement of magnitude, Δd, in the same direction as the displacement. In this case, the engine does positive mechanical work on the motorcycle, since the displacement is in the same direction as the force. The net force is the sum of the applied force produced by the engine, the normal force, the force of gravity, the force of friction between the wheels and the road, and the force of friction between the air and the vehicle (including the motorcyclist).

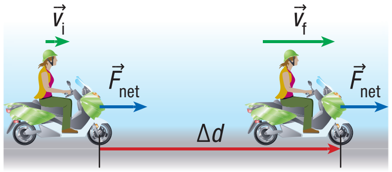


Figure 2 Displacement of a motorcycle accelerating on a flat, level roadway

The work equation may be used to describe the relationship between the total, or net, work done on the motorcycle, the magnitude of the net force and the displacement, and the angle between the applied force and the displacement:

$$W_{net} = F_{net}(\cos\theta)\Delta d$$

Since the force and displacement are in the same direction, $\cos\theta = 0°$ and $W = F_{net}\Delta d$.

Newton's second law relates the magnitude of the net force to the motorcycle's mass and the magnitude of its resulting acceleration:

$$F_{net} = ma$$

Substituting ma for F_{net} in the work equation gives

$$W_{net} = ma\Delta d$$

In Chapter 1, you learned that the following equation relates the final speed of an accelerating object to its initial speed and the magnitudes of its acceleration and displacement:

$$v_f^2 = v_i^2 + 2a\Delta d$$

Isolating $a\Delta d$ on the left side of this equation, we get

$$a\Delta d = \frac{v_f^2 - v_i^2}{2}$$

Substituting $\frac{v_f^2 - v_i^2}{2}$ for $a\Delta d$ in the equation $W_{net} = ma\Delta d$, we get

$$W_{net} = m\left(\frac{v_f^2 - v_i^2}{2}\right) \text{ or } W_{net} = \frac{mv_f^2}{2} - \frac{mv_i^2}{2}$$

If we assume that the motorcycle accelerates from rest to v, then $v_i = 0$ m/s and $v_f = v$:

$$W_{net} = \frac{mv^2}{2} - 0$$

$$W_{net} = \frac{mv^2}{2}$$

The quantity $\frac{mv^2}{2}$ is equal to the net amount of work done on the motorcycle to cause it to reach a final speed of v and also equals the amount of kinetic energy the motorcycle possesses as it travels at a speed of v. Therefore, in general, an object of mass, m, travelling at a constant speed, v, has a kinetic energy, E_k, given by the equation

$$\boxed{E_k = \frac{mv^2}{2}}$$

Kinetic energy is a scalar quantity: it has a magnitude given by the equation above, but it does not have a direction. If mass is measured in kilograms and speed in metres per second, then E_k will have units of $\frac{\text{kg}\cdot\text{m}^2}{\text{s}^2}$. The unit $\frac{\text{kg}\cdot\text{m}^2}{\text{s}^2}$ may be simplified as follows:

$$\frac{\text{kg}\cdot\text{m}^2}{\text{s}^2} = \left(\frac{\text{kg}\cdot\text{m}}{\text{s}^2}\right)\text{m} = \text{N}\cdot\text{m}$$

As you learned in Section 5.1,

$$1\ \text{N}\cdot\text{m} = 1\ \text{J}$$

Therefore, both kinetic energy and mechanical work may be quantified in units of joules, J. This indicates the close relationship between mechanical work and kinetic energy. We will use the kinetic energy equation in the following Tutorial.

Tutorial 1 Calculating the Kinetic Energy of a Moving Object

In this Tutorial, you will use the equation $E_k = \frac{mv^2}{2}$ to calculate the kinetic energy of an object of mass, m, moving at a constant speed, v.

Sample Problem 1

Calculate the kinetic energy of a 150 g baseball that is travelling toward home plate at a constant speed of 35 m/s.

Given: $m = 150$ g or 0.150 kg; $v = 35$ m/s

Required: E_k, kinetic energy

Analysis: $E_k = \frac{mv^2}{2}$

Solution:

$$E_k = \frac{mv^2}{2}$$

$$= \frac{(0.150\ \text{kg})(35\ \text{m/s})^2}{2}$$

$$E_k = 92\ \text{J}$$

Statement: The baseball has a kinetic energy of 92 J.

Practice

1. A 70.0 kg athlete is running at 12 m/s in the 100.0 m dash. What is the kinetic energy of the athlete? T/I [ans: 5.0 kJ]
2. A dynamics cart has a kinetic energy of 4.2 J when moving across a floor at 5.0 m/s. What is the mass of the cart? T/I [ans: 0.34 kg]
3. A 150 g bird goes into a dive, reaching a kinetic energy of 30.0 J. What is the speed of the bird? T/I [ans: 20 m/s]

The Relationship between Mechanical Work and Kinetic Energy

You can observe the relationship between mechanical work and kinetic energy by analyzing the mechanical work and kinetic energy equations. Since $E_k = \frac{mv^2}{2}$, the equation $W_{net} = \frac{mv_f^2}{2} - \frac{mv_i^2}{2}$ may be written as $W_{net} = E_{k_f} - E_{k_i}$ or $W_{net} = \Delta E_k$, where E_{k_f} is the final kinetic energy and E_{k_i} is the initial kinetic energy of the object. In words, this equation tells us that the total mechanical work, W, that increases the speed of an object is equal to the change in the object's kinetic energy, $E_{k_f} - E_{k_i}$. In other words, work is a change in energy. This relationship between kinetic energy and mechanical work is known as the **work–energy principle**.

work–energy principle the net amount of mechanical work done on an object equals the object's change in kinetic energy

Tutorial 2 Solving Problems Using the Work–Energy Principle

In the following Sample Problem, you will use the work–energy principle to determine the final speed of a hockey puck that is being pushed by a hockey stick.

Sample Problem 1

A 165 g hockey puck initially at rest is pushed by a hockey stick on a slippery horizontal ice surface by a constant horizontal force of magnitude 5.0 N (assume that the ice is frictionless), as shown in **Figure 3**. What is the puck's speed after it has moved 0.50 m?

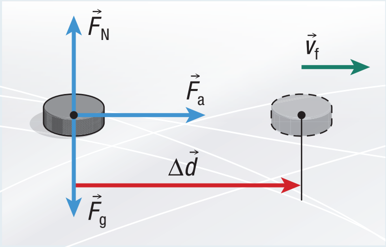


Figure 3

Consider the diagram shown in Figure 3. In this problem, the gravitational force and the normal force are equal in magnitude and opposite in direction. Therefore, they cancel each other. Since there is no friction, the magnitude of the net force on the puck is equal to the magnitude of the applied force, $\vec{F}_a$, directed horizontally. Since the net force is in the same direction as the displacement, we may use the equation $W_{net} = F_{net}\Delta d$ to calculate the total work done on the puck. We may then use the equation $W_{net} = \frac{mv_f^2}{2} - \frac{mv_i^2}{2}$ to calculate the puck's final speed, v_f.

Given: $m = 0.165$ kg; $F_a = 5.0$ N; $\Delta d = 0.50$ m; $v_i = 0$ m/s

Required: v_f, the puck's final speed

Analysis: $W_{net} = F_{net}\Delta d$; $W_{net} = \frac{mv_f^2}{2} - \frac{mv_i^2}{2}$

Solution:
$$\begin{aligned} W_{net} &= F_a\Delta d \\ &= (5.0\ \text{N})(0.50\ \text{m}) \\ &= 2.5\ \text{N}\cdot\text{m} \\ W_{net} &= 2.5\ \text{J} \end{aligned}$$

Now that we have calculated the net work done on the puck, we can use this value to find the puck's final velocity.

$$\begin{aligned} W_{net} &= \frac{mv_f^2}{2} - \frac{mv_i^2}{2} \\ W_{net} &= \frac{mv_f^2}{2} - 0 \\ v_f^2 &= \frac{2W_{net}}{m} \\ v_f &= \sqrt{\frac{2W_{net}}{m}} \\ &= \sqrt{\frac{2(2.5\ \text{J})}{0.165\ \text{kg}}} \\ v_f &= 5.5\ \text{m/s} \end{aligned}$$

Statement: The hockey puck's final speed is 5.5 m/s.

Practice

1. A 1300 kg car starts from rest at a stoplight and accelerates to a speed of 14 m/s over a displacement of 82 m. T/I
   (a) Calculate the net work done on the car. [ans: 130 kJ]
   (b) Calculate the net force acting on the car. [ans: 1.6×10^3 N]
2. A 52 kg ice hockey player moving at 11 m/s slows down and stops over a displacement of 8.0 m. T/I C
   (a) Calculate the net force on the skater. [ans: 390 N [backwards]]
   (b) Give two reasons why you can predict that the net work on the skater must be negative.

Kinetic energy is the energy possessed by moving objects. The work–energy principle tells us that the change in an object's kinetic energy is equal to the total amount of work done on that object. However, kinetic energy is not the only type of energy an object may have. Objects may possess another form of energy.

Gravitational Potential Energy: A Stored Type of Energy

In a circus stunt, one acrobat stands on a platform at the top of a tower ready to jump onto one end of a seesaw. Another acrobat stands on the other end. When the acrobat on the tower steps off his platform, the force of gravity pulls him downward, and he accelerates toward the seesaw. Just before landing, the acrobat is moving very quickly and has a lot of kinetic energy. This kinetic energy allows the acrobat to do mechanical work on his end of the seesaw, displacing it downward. This downward motion causes the other acrobat to be thrown into the air (**Figure 4**).

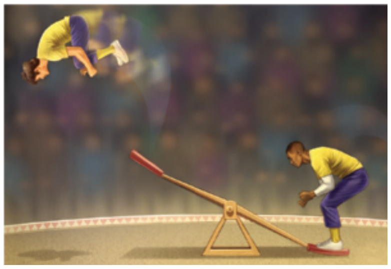


Figure 4 The acrobat's kinetic energy does mechanical work on the seesaw, causing the other acrobat to be displaced into the air.

When the acrobat was at the top of the tower, he was at rest and did not have kinetic energy. However, since he was positioned high above the ground, he had the ability to fall and gain kinetic energy that could do mechanical work. He was able to fall because of the force of gravity on him. The ability of an object to do work because of forces in its environment is called **potential energy**. Potential energy may be considered a stored form of energy. The force acting on the acrobat as he fell is Earth's gravitational force. Therefore, we say that the acrobat had **gravitational potential energy** when he was above the ground because of his position. The acrobat's gravitational potential energy started turning into kinetic energy as soon as he began to fall. A ski racer perched at the top of a ski hill, the water at the top of a waterfall, and a space shuttle orbiting Earth all have gravitational potential energy (**Figure 5**).

potential energy a form of energy an object possesses because of its position in relation to forces in its environment

gravitational potential energy energy possessed by an object due to its position relative to the surface of Earth

Figure 5 (a) A downhill skier, (b) the water at the top of Niagara Falls, and (c) the orbiting space shuttle all have gravitational potential energy.

Quantifying Gravitational Potential Energy

Have you ever heard the expression "the higher you go, the harder you fall"? In physics, this means that objects can do more work on other objects if they fall from higher positions above a particular **reference level**, or the level to which an object may fall. Any level close to Earth's surface may be used as a reference level. The selected reference level is assigned a gravitational potential energy value of 0 J, and levels above it have positive values (greater than 0 J). Levels below the reference level have negative values (less than 0 J).

reference level a designated level to which objects may fall; considered to have a gravitational potential energy value of 0 J

Gravitational potential energy may be calculated using the equation $E_g = mgh$ (where $g = 9.8\ \text{m/s}^2$) only near Earth's surface because the value of g changes as you move farther away from (or closer to) Earth's centre. The value of g is about $9.8\ \text{m/s}^2$ near Earth's surface. However, the value steadily decreases to approximately $8.5\ \text{m/s}^2$ at 400 km above Earth's surface (height of a space shuttle orbit) and increases to about $10.8\ \text{m/s}^2$ at a depth of 3000 km below the surface.

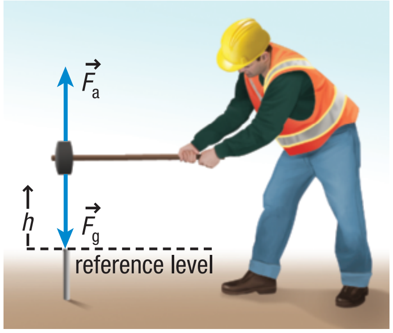


Figure 6 A construction worker uses a sledgehammer.

Assume that a construction worker needs to drive a spike into the ground with a sledgehammer (**Figure 6**). To do this, the worker must first raise the hammer and then allow it to fall onto the spike. If we assume the top of the spike to be our reference level, then the distance from the top of the spike to the hammer's head is the height, *h*. The weight of the hammer is given by the magnitude of $\vec{F}_g$ and is equal to *mg*, where *m* is the hammer's mass and *g* is the magnitude of the gravitational force constant, 9.8 N/kg.

If the construction worker (CW) lifts the hammer straight up at constant speed, then he applies a force $\vec{F}_{cw}$ upward that is equal in magnitude to the weight of the hammer, *mg*. In lifting the hammer, the worker is doing work given by $W_{cw} = F_{cw}\Delta d$ since the applied force and the displacement are in the same direction. Therefore, the work done by the construction worker on the hammer is $W_{cw} = mgh$ since $F_{cw} = mg$ and $\Delta d = h$. This mechanical work serves to transfer energy from the construction worker to the hammer, increasing the hammer's gravitational potential energy. The change in the hammer's gravitational potential energy is equal to the work done by the construction worker: $E_g = mgh$.

Note that the hammer is raised at constant speed ($v_i = v_f$). The construction worker does work on the hammer, but the force of gravity also does work on the hammer, equal to $W_g = F_g(\cos 180°)\Delta d$, or $W_g = mgh(-1)$.

In general, the gravitational potential energy of an object of mass, *m*, lifted to a height, *h*, above a reference level is given by the following equation:

$$E_g = mgh$$

The SI unit for gravitational potential energy is the newton metre, or the joule—the same SI unit used for kinetic energy and all other forms of energy. As with kinetic energy and work, gravitational potential energy is a scalar quantity.

Tutorial 3 Determining Gravitational Potiential Energy

In this Tutorial, we will determine the gravitational potential energy of a person on a drop tower amusement park ride. In a drop tower ride, people sit in gondola seats that are lifted to the top of a vertical structure and then dropped to the ground. Special brakes are used to slow the gondolas down just before they reach the ground.

Sample Problem 1

What is the gravitational potential energy of a 48 kg student at the top of a 110 m high drop tower ride relative to the ground?

In this Sample Problem, the student's mass and height above ground (the reference level) are given. Therefore, we may use the gravitational potential energy equation, $E_g = mgh$, to calculate the student's gravitational potential energy.

Given: $m = 48$ kg; $h = 110$ m; $g = 9.8$ N/kg

Required: E_g, gravitational potential energy

Analysis: $E_g = mgh$

Solution: $E_g = mgh$

$$= (48\ \cancel{\text{kg}})\left(9.8\ \frac{\text{N}}{\cancel{\text{kg}}}\right)(110\ \text{m})$$

$$= 5.2 \times 10^4\ \text{N}\cdot\text{m}$$

$$E_g = 5.2 \times 10^4\ \text{J or 52 kJ}$$

Statement: The student has 52 kJ of gravitational potential energy at the top of the ride relative to the ground.

Practice

1. A 58 kg person walks down the flight of stairs shown in **Figure 7**. Use the ground as the reference level. T/I
   (a) Calculate the person's gravitational potential energy at the top of the stairs, on the landing, and at ground level. [ans: 3400 J, 1700 J, 0 J]
   (b) What happens to gravitational potential energy as you go down a flight of stairs? What happens to gravitational potential energy as you climb a flight of stairs?

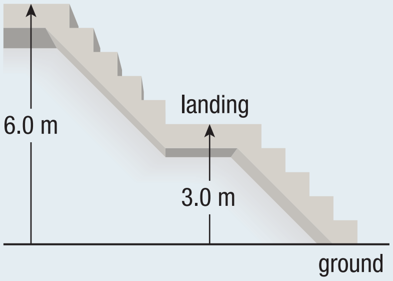


Figure 7

Mechanical Energy

Objects may possess kinetic energy only, gravitational potential energy only, or a combination of kinetic energy and gravitational potential energy relative to a particular reference level. For example, a hockey puck sliding on a flat ice surface at ground level has kinetic energy but no gravitational potential energy. An acorn hanging on a tree branch has gravitational potential energy but no kinetic energy. A parachutist descending to the ground has kinetic energy and gravitational potential energy.

The sum of an object's kinetic energy and gravitational potential energy is called **mechanical energy**. Therefore, if a sliding hockey puck has 10 J of kinetic energy and no gravitational potential energy, then it has 10 J of mechanical energy. If a descending parachutist has 5 kJ of kinetic energy and 250 kJ of gravitational potential energy, then the parachutist has 255 kJ of mechanical energy.

mechanical energy the sum of kinetic energy and gravitational potential energy

5.2 Summary

- Energy is the capacity (ability) to do work.
- Kinetic energy is energy possessed by moving objects. The kinetic energy of an object with mass, m, and speed, v, is given by $E_k = \frac{mv^2}{2}$.
- The total work, W_{net}, done on an object results in a change in the object's kinetic energy: $W_{net} = E_{k_f} - E_{k_i}$, where E_{k_f} and E_{k_i} represent the final and initial kinetic energy of the object, respectively. In other words, $W_{net} = \Delta E_k$.
- Gravitational potential energy is possessed by an object based on its position relative to a reference level, which is often the ground. $E_g = mgh$, where h is the height above the chosen reference level.
- Mechanical energy is the sum of kinetic energy and gravitational potential energy.

Investigation **5.2.1**

Conservation of Energy (p. 257)
In this investigation, you will explore what happens to the gravitational potential energy, kinetic energy, and total mechanical energy of a cart as it rolls down a ramp.

5.2 Questions

1. A bobsleigh with four people on board has a total mass of 610 kg. How fast is the sleigh moving if it has a kinetic energy of 40.0 kJ? T/I
2. A 0.160 kg hockey puck starts from rest and reaches a speed of 22 m/s when a hockey stick pushes on it for 1.2 m during a shot. T/I
   (a) What is the final kinetic energy of the puck?
   (b) Determine the average net force on the puck using two different methods.
3. A large slide is shown in **Figure 8**. A person with a mass of 42 kg starts from rest on the slide at position A and then slides down to positions B, C, and D. Complete the following using the ground as the reference level: T/I

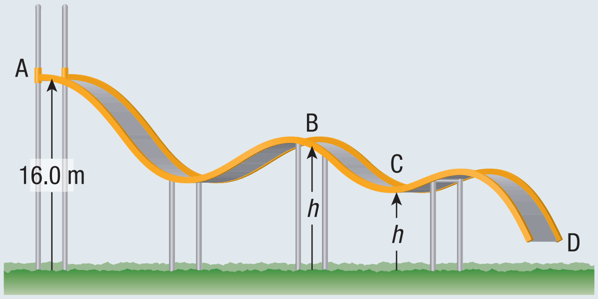


Figure 8

   (a) Calculate the gravitational potential energy of the person at position A.
   (b) The person has a gravitational potential energy of 4500 J at position B. How high above the ground is the person at position B?
   (c) The person loses 4900 J of gravitational potential energy when she moves from A to C. How high is the person at C?
   (d) What is the person's gravitational potential energy at ground level at D?
4. Forty 2.0 kg blocks 20.0 cm thick are used to make a retaining wall in a backyard. Each row of the wall will contain 10 blocks. You may assume that the first block is placed at the reference level. How much gravitational potential energy is stored in the wall when the blocks are set in place? T/I
5. You throw a basketball straight up into the air. Describe what happens to the kinetic energy and gravitational potential energy of the ball as it moves up and back down until it hits the floor. K/U C
6. Using the terms *work*, *kinetic energy*, and *gravitational potential energy*, describe what happens to people in a drop tower ride as they are slowly pulled to the top, released, and then safely slowed down at the bottom. K/U C

5.3 Types of Energy and the Law of Conservation of Energy

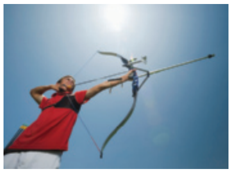
You use mechanical energy (a combination of kinetic energy and gravitational potential energy) to do mechanical work every day. Is mechanical energy the only type of energy? In fact, there are many types of energy in the universe, all of which involve kinetic energy, potential energy, or both. Different types of energy have different names. **Table 1** describes some different types of energy.

thermal energy the total quantity of kinetic and potential energy possessed by the atoms or molecules of a substance

Table 1 Types of Energy

Type of energy	Form (kinetic, potential, or both)	Description	Application/Example
mechanical energy	potential and kinetic	energy possessed by objects that are primarily affected by the force of gravity and frictional forces	
gravitational energy	potential	energy possessed by objects that are affected by the force of gravity; applies to all objects on Earth (and the universe)	
radiant energy (also known as light, light energy, or electromagnetic radiation)	potential and kinetic	energy possessed by oscillating electric and magnetic fields	
electrical energy (static electricity)	potential	energy possessed by accumulated static charges	
electrical energy (current electricity)	potential and kinetic	energy possessed by flowing charges (you will learn more about this in Chapter 11)	
thermal energy (sometimes incorrectly called heat energy)	potential and kinetic	energy possessed by randomly moving atoms and molecules (you will learn more about this in Chapter 6)	
sound energy	potential and kinetic	energy possessed by large groups of oscillating atoms and molecules	

Table 1 (continued)

nuclear energy (also known as atomic energy)	potential	energy possessed by protons and neutrons in atomic nuclei (you will learn more about this in Chapter 7)	
elastic energy (also known as spring energy)	potential	energy possessed by materials that are stretched, compressed, or twisted and tend to return to their original shape	
chemical energy (also known as bond energy, fuel energy, food energy, molecular energy, and internal energy)	potential	energy associated with bonds in molecules	

nuclear energy potential energy of protons and neutrons in atomic nuclei

Energy Transformations

The conversion of energy is called an **energy transformation**: the change of one form or type of energy into another. For example, photosynthesis is a process involving energy transformations in a plant. In photosynthesis, plants transform radiant energy into the chemical energy stored in food molecules (food energy) such as glucose (a sugar) and starch. In the process, some of the radiant energy is also transformed into thermal energy. Animals, including humans, eat plants and transform the chemical energy in the plants into chemical energy in their muscles. Muscles then transform this chemical energy into the kinetic energy of moving limbs, which do work on objects in the environment.

Technological systems also transform energy from one form into another. For example, an electric light bulb transforms electrical energy into radiant energy (light) and thermal energy (**Figure 1**). The internal combustion engine transforms the chemical energy in fuels such as gasoline and diesel into the kinetic energy of moving cars, motorcycles, trains, buses, and boats (**Figure 2**). In all of these processes, a lot of thermal energy is also produced and emitted into the environment.

energy transformation the change of one type of energy into another

Figure 1 A light bulb transforms electrical energy into radiant energy and thermal energy.

The Law of Conservation of Energy

People often wonder how much energy there is in the universe and whether we will eventually run out of energy. Scientists have studied energy and energy transformations and have arrived at some important generalizations. For example, they noticed that when one form of energy is transformed into another form (or forms) of energy, the quantity of one form is reduced by the same amount that the quantity of the other form (or forms) is increased. This suggests that, in an energy transformation, the total amount of energy does not change but remains constant. For example, a light bulb may transform 100 J of electrical energy into 5 J of radiant energy and 95 J of thermal energy. The total amount of energy has not changed:

$$\text{100 J of electrical energy} = \text{95 J of thermal energy} + \text{5 J of radiant energy}$$

$$\text{100 J of energy} = \text{100 J of energy}$$

Figure 2 A gasoline engine transforms the chemical energy in gasoline into kinetic energy, thermal energy, and sound energy.

law of conservation of energy energy is neither created nor destroyed; when energy is transformed from one form into another, no energy is lost

This generalization, known as the **law of conservation of energy**, is stated as follows:

> **Law of Conservation of Energy**
> The total amount of energy in the universe is conserved. There is a certain total amount of energy in the universe, and this total never changes. New energy cannot be created out of nothing, and existing energy cannot disappear; the energy that exists can only be changed from one form into another. When an energy transformation occurs, no energy is lost.

Quantifying Energy Transformations

Evidence of the law of conservation of energy is all around us, but to notice it, you need to take measurements and perform simple calculations. Let us see how the law is demonstrated when a 65.0 kg diver performs a handstand dive from a 10.0 m high diving platform into the water below.

Let us analyze the dive in terms of the diver's potential energy, E_g, kinetic energy, E_k, and total mechanical energy, E_m, which is the sum of E_g and E_k. We will calculate these values for three phases of the dive occurring at three distinct moments in time: the phase before the diver leaves the platform, the phase when the diver has travelled half the distance to the water's surface, and the phase when the diver's fingers reach the water's surface. We will assume that the water's surface is the reference level, where $E_g = 0$ J.

Phase 1: Before the Dive

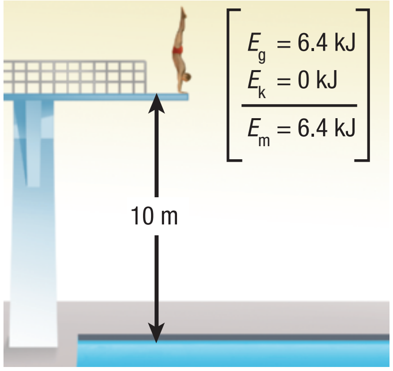


Figure 3 Phase 1: before the dive

The diver begins the dive in a handstand position on the platform of the diving tower (**Figure 3**). Since he is motionless, the diver's kinetic energy is equal to zero ($E_k = 0$ kJ), and his gravitational potential energy is calculated as follows:

$$E_g = mgh$$

$$= (65\ \cancel{\text{kg}})\left(9.8\ \frac{\text{N}}{\cancel{\text{kg}}}\right)(10.0\ \text{m})$$

$$E_g = 6.4 \times 10^3\ \text{J or } 6.4\ \text{kJ (two extra digits carried)}$$

At this point in the dive, the diver's kinetic energy is equal to 0 J and his potential energy is equal to 6.4 kJ. The diver's total mechanical energy is equal to 6.4 kJ, the sum of his gravitational potential energy and his kinetic energy:

$$E_m = E_g + E_k$$

$$= 6.4\ \text{kJ} + 0\ \text{kJ}$$

$$E_m = 6.4\ \text{kJ}$$

Phase 2: At the Halfway Point

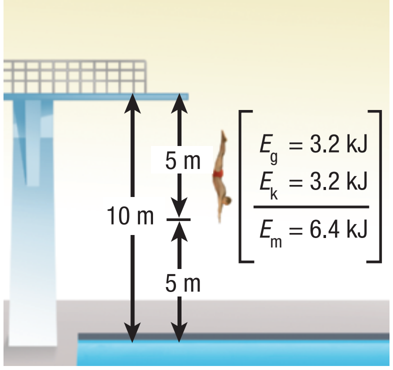


Figure 4 Phase 2: at the halfway point

When the diver leaves the platform, he will accelerate toward the water at 9.8 m/s^2 (assuming negligible friction with the air). At the halfway point, the diver is 5.0 m above the water's surface (**Figure 4**). At this point in the dive, the diver's gravitational potential energy may be calculated as follows:

$$E_g = mgh$$

$$= (65\ \cancel{\text{kg}})\left(9.8\ \frac{\text{N}}{\cancel{\text{kg}}}\right)(5.0\ \text{m})$$

$$E_g = 3.2 \times 10^3\ \text{J or } 3.2\ \text{kJ}$$

At the halfway point, the diver's kinetic energy may be calculated using the equation $E_k = \frac{mv^2}{2}$. This equation requires us to determine the diver's speed, v, at the halfway point in the dive.

Since the diver accelerates as he descends, we may use the equation $v_f^2 = v_i^2 + 2a\Delta d$ for this purpose. Since v_f in the equation $v_f^2 = v_i^2 + 2a\Delta d$ and v in the equation $E_k = \frac{mv^2}{2}$ both represent the diver's speed at this point in the dive, we will use the symbol v (not v_f) to represent the diver's speed. Thus,

$$\begin{aligned} v^2 &= v_i^2 + 2a\Delta d \\ v &= \sqrt{v_i^2 + 2a\Delta d} \\ &= \sqrt{2a\Delta d} \text{ since } v_i = 0 \text{ m/s} \\ &= \sqrt{2(9.8 \text{ m/s}^2)(5.0 \text{ m})} \\ v &= 9.899 \text{ m/s (two extra digits carried)} \end{aligned}$$

Substituting $v = 9.899$ m/s into the equation $E_k = \frac{mv^2}{2}$ gives

$$\begin{aligned} E_k &= \frac{mv^2}{2} \\ &= \frac{(65 \text{ kg})(9.899 \text{ m/s})^2}{2} \\ E_k &= 3.2 \times 10^3 \text{ J or } 3.2 \text{ kJ} \end{aligned}$$

At the halfway point, the diver's total mechanical energy is

$$\begin{aligned} E_g &= E_g + E_k \\ &= 3.2 \text{ kJ} + 3.2 \text{ kJ} \\ E_m &= 6.4 \text{ kJ} \end{aligned}$$

The total mechanical energy is the same at this point in the dive as it was before the dive.

Phase 3: At the Water's Surface

When the diver reaches the surface of the water, his height above the water is 0 m (**Figure 5**). Thus, $E_g = 0$ J since $E_g = mgh$ and $h = 0$ m. By this point, the diver has been accelerating for the full distance between the platform and the water. His kinetic energy is calculated as in Phase 2:

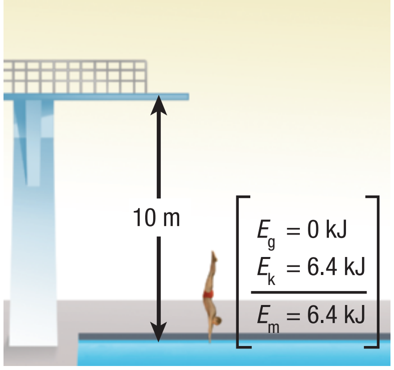


Figure 5 Phase 3: at the water's surface

$$\begin{aligned} v_f &= \sqrt{v_i^2 + 2a\Delta d} \\ &= \sqrt{2a\Delta d}, \text{ since } v_i = 0 \text{ m/s} \\ &= \sqrt{2(9.8 \text{ m/s}^2)(10.0 \text{ m})} \\ v_f &= 14 \text{ m/s} \end{aligned}$$

$$\begin{aligned} E_k &= \frac{mv^2}{2} \\ &= \frac{(65 \text{ kg})(14 \text{ m/s})^2}{2} \\ E_k &= 6.4 \text{ kJ} \end{aligned}$$

At the water's surface, the diver's total mechanical energy is

$$\begin{aligned} E_m &= E_g + E_k \\ &= 0 \text{ kJ} + 6.4 \text{ kJ} \\ E_m &= 6.4 \text{ kJ} \end{aligned}$$

The total mechanical energy is the same at this point in the dive as it was just before the dive and at the halfway point. You can assume that the diver possesses the same total mechanical energy throughout the dive. You can check this assumption by performing similar calculations at different phases of the dive.

The example of the diver illustrates the law of conservation of energy by showing that while the diver's gravitational potential energy was transformed into kinetic energy throughout the dive, his total mechanical energy did not change—it was conserved. The law of conservation of energy is an important fundamental law of nature that can help us solve many problems in everyday life.

Tutorial 1 Applying the Law of Conservation of Energy

The law of conservation of energy may be used to solve problems involving energy transformations. In the following Sample Problem, we will analyze the energy transformations that occur when an object (a camera in this case) falls to the ground.

Sample Problem 1

A 1.1 kg camera slips out of a photographer's hands while he is taking a photograph. The camera falls 1.4 m to the ground below.

(a) What is the camera's gravitational potential energy relative to the ground when it is in the photographer's hands?

(b) Using the law of conservation of energy, determine the camera's kinetic energy at the instant it hits the ground.

(c) Use the camera's kinetic energy to determine its speed at the instant it hits the ground.

Solution

(a) **Given:** $m = 1.1$ kg; $h = 1.4$ m

Required: E_g, gravitational potential energy

Analysis: $E_g = mgh$

Solution:

$$\begin{aligned} E_g &= mgh \\ &= (1.1\ \cancel{\text{kg}})\left(9.8\ \frac{\text{N}}{\cancel{\text{kg}}}\right)(1.4\ \text{m}) \\ &= 15\ \text{N}\cdot\text{m} \\ E_g &= 15\ \text{J} \end{aligned}$$

Statement: The camera has 15 J of gravitational potential energy relative to the ground when it is in the photographer's hands.

(b) We know that the camera has 0 J of kinetic energy when it is in the photographer's hands since it is not moving at that time. Using the mechanical energy equation, $E_m = E_g + E_k$, we may show that the camera has 15 J of total mechanical energy, E_m, at this time since

$$\begin{aligned} E_m &= E_g + E_k \\ &= 15\ \text{J} + 0\ \text{J} \\ E_m &= 15\ \text{J} \end{aligned}$$

According to the law of conservation of energy, the camera will have the same total mechanical energy for its entire fall. However, as the camera falls, its gravitational potential energy is transformed into kinetic energy. The camera will continuously lose gravitational potential energy as it gains kinetic energy. At the instant it hits the ground, the camera will have only kinetic energy since it is now at the reference level ($h = 0$) and its gravitational potential energy is zero. We may use the mechanical energy equation, $E_m = E_g + E_k$, to calculate the camera's kinetic energy at the instant it hits the ground:

$$\begin{aligned} E_m &= E_g + E_k \\ E_k &= E_m - E_g \\ &= 15\ \text{J} - 0\ \text{J} \\ E_k &= 15\ \text{J} \end{aligned}$$

The camera has 15 J of kinetic energy when it hits the ground.

(c) Since we know the camera's mass, m, and the kinetic energy, E_k, it has when it hits the ground, we may use the kinetic energy equation, $E_k = \frac{mv^2}{2}$, to determine the camera's speed, v, when it hits the ground.

Given: $E_k = 15$ J; $m = 1.1$ kg

Required: v, speed

Analysis: $E_k = \frac{mv^2}{2}$

Solution:

$$\begin{aligned} E_k &= \frac{mv^2}{2} \\ v &= \sqrt{\frac{2E_k}{m}} \\ &= \sqrt{\frac{2(15\ \text{J})}{1.1\ \text{kg}}} \\ v &= 5.2\ \text{m/s} \end{aligned}$$

Statement: The camera has a speed of 5.2 m/s when it hits the ground.

The camera's speed may also be calculated using the kinematic equations used earlier in this section. Try this approach to check the calculation performed here.

Practice

1. A 0.20 kg ball is thrown straight up from the edge of a 30.0 m tall building at a velocity of 22.0 m/s. The ball moves up to the maximum height and then falls to the ground at the base of the building. Use the law of conservation of energy to answer the following questions, assuming that the reference level for gravitational potential energy is ground level. T/I
    (a) What is the total energy of the ball at the start when it had a velocity of 22.0 m/s? [ans: 110 J]
    (b) What is the velocity of the ball at the maximum height? What is the maximum height of the ball? [ans: 0 m/s [up], 55 m]
    (c) What is the velocity of the ball when it hits the ground? [ans: 33 m/s [down]]

5.3 Summary

- Energy exists in many forms.
- In an energy transformation, energy changes from one form into another.
- The law of conservation of energy states that when energy is changed from one form into another, no energy is lost.
- When using the law of conservation of energy to solve problems, you may find the total mechanical energy, E_m, at one point in the motion of the object and then equate it to the total mechanical energy at another point. The total mechanical energy is $E_m = E_g + E_k$.

5.3 Questions

1. Describe the energy transformations occurring in each of the following situations: K/U
    (a) A ball falls from the top of a building.
    (b) An archer pulls a bow back and releases the arrow.
    (c) A firework explodes.
    (d) An incandescent light bulb comes on.
    (e) A gasoline lawnmower cuts the lawn.
2. A golf ball of mass 45.9 g is launched from a height of 8.0 m above the level of the green at a speed of 20.0 m/s. At the maximum height above the green, the ball is moving at 12 m/s. Assume there is no air resistance acting on the ball. Calculate the following for the golf ball: T/I
    (a) the total mechanical energy at the start (assume the level of the green to be the reference level)
    (b) the maximum height of the ball above the green
    (c) the speed of the ball when it strikes the green
3. Many roller coasters have loops where carts roll on a track that curves sharply up into the air. At the top, the people are upside down (and usually screaming). For safety reasons, many of these roller coasters must have a minimum speed at the top of the loop. In the roller coaster shown in **Figure 6**, the cart must have a minimum speed of 10.0 m/s at the top of the loop to make it around safely. Assuming that the roller coaster starts from rest at the top of the first hill and there is no friction on the roller coaster, what is the minimum height of the first hill? T/I

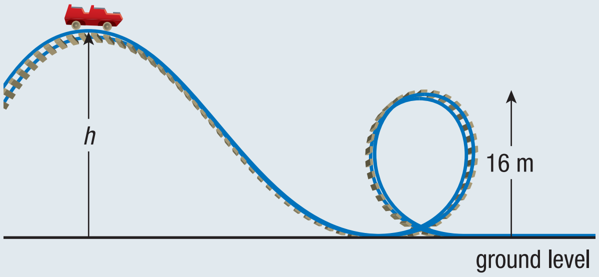


Figure 6

4. A net force acts on an object initially at rest, giving it an acceleration, a, while moving it a distance, Δd, forward across a horizontal surface. T/I C
    (a) Use kinematics equations to show that $v^2 = 2a\Delta d$.
    (b) The final total mechanical energy is $E_k = \frac{mv^2}{2}$.
    Substitute the equation for the final velocity into the equation for the final kinetic energy and simplify. What does this new equation prove?

5.4 Efficiency, Energy Sources, and Energy Conservation

Electric light bulbs were invented over 150 years ago. Today, billions of light bulbs (lamps) illuminate vast areas of Earth at night (**Figure 1**). Light bulbs transform electrical energy into radiant energy and thermal energy.

Figure 1 Large areas of Earth are illuminated by incandescent light bulbs at night.

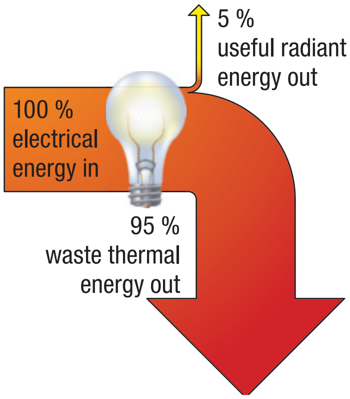


Figure 2 Incandescent light bulbs transform a very small percentage of the electrical energy supplied into radiant energy. Therefore, incandescent bulbs produce a lot of thermal energy waste.

Have you ever noticed how hot incandescent light bulbs get? Typical incandescent bulbs transform only about 5 % of the electrical energy delivered to the bulbs into radiant energy. The other 95 % of the electrical energy is transformed into thermal energy (**Figure 2**). We say that incandescent light bulbs are 5 % efficient at converting electrical energy (the supplied energy) into radiant energy (the desired energy). Since we use light bulbs for illumination, not heating, the thermal energy produced is considered to be waste energy or lost energy.

Efficiency

efficiency the amount of useful energy produced in an energy transformation expressed as a percentage of the total amount of energy used

Efficiency is the ratio of the amount of useful energy produced (energy output, or E_{out}) to the amount of energy used (energy input, or E_{in}), expressed as a percentage. Efficiency is calculated as follows:

$$\text{efficiency} = \frac{E_{\text{out}}}{E_{\text{in}}} \times 100\ \%$$

Tutorial 1 Using the Efficiency Equation

The efficiency equation may be used to calculate the efficiency of transforming one form of energy into another, or the efficiency with which work changes an object's gravitational potential energy or kinetic energy. In the first Sample Problem of this Tutorial, you will calculate the efficiency of transforming one form of energy into another. In the second Sample Problem, you will calculate the efficiency with which a machine transforms mechanical work into gravitational potential energy.

Sample Problem 1

A firefly's body transforms chemical energy in food into radiant energy that appears as a greenish glow in its abdomen (**Figure 3** on the next page). Fireflies use this glow to attract mates or prey. What is a firefly's efficiency if its body transforms 4.13 J of chemical energy into 3.63 J of radiant energy?

Since we are given the amounts of energy used and produced, we may use the efficiency equation to calculate the efficiency with which the firefly's body transforms chemical energy into radiant energy.

Figure 3 A firefly can transform chemical energy into radiant energy.

Given: $E_{\text{in}} = 4.13$ J (chemical); $E_{\text{out}} = 3.63$ J (radiant)

Required: efficiency

Analysis: $\text{efficiency} = \dfrac{E_{\text{out}}}{E_{\text{in}}} \times 100\ \%$

Solution:
$$\begin{aligned}\text{efficiency} &= \frac{E_{\text{out}}}{E_{\text{in}}} \times 100\ \% \\ &= \frac{3.63\ \cancel{\text{kJ}}}{4.13\ \cancel{\text{kJ}}} \times 100\ \% \\ \text{efficiency} &= 88\ \%\end{aligned}$$

Statement: The firefly's body transforms chemical energy into radiant energy with 88 % efficiency.

Sample Problem 2

What is the efficiency of a rope-and-pulley system if a painter uses 1.93 kJ of mechanical energy to pull on the rope and lift a 20.0 kg paint barrel at constant speed to a height of 7.5 m above the ground (**Figure 4**)?

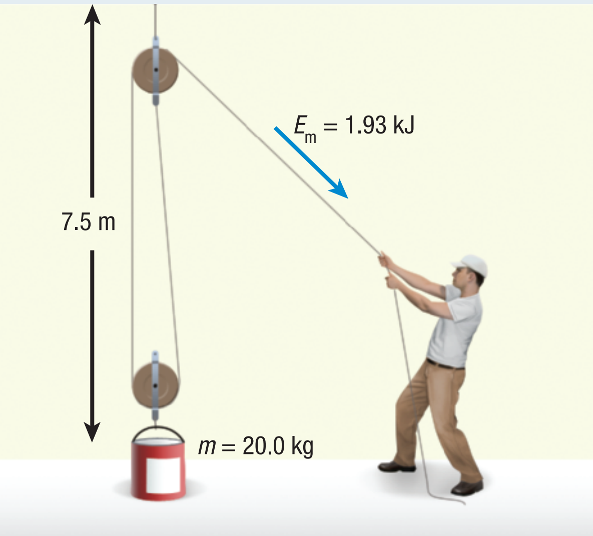


Figure 4 What is the efficiency of this rope-and-pulley system?

In this question, the input energy is the energy the painter uses to pull on the rope. You are not given the output energy, so you cannot use the efficiency equation right away. As the painter pulls on the rope, the paint barrel moves higher and gains gravitational potential energy. The painter's mechanical energy is transformed into gravitational potential energy. Therefore, E_g is the output energy, E_{out}. We may calculate the barrel's gravitational potential energy when it is 7.5 m above the ground by using the equation $E_g = mgh$.

Given: $E_{\text{in}} = 1.93$ kJ or 1.93×10^3 J; $m = 20.0$ kg; $h = 7.5$ m; $g = 9.8$ N/kg

Required: E_g, E_{out}, efficiency

Analysis: $E_g = mgh$ and $\text{efficiency} = \dfrac{E_{\text{out}}}{E_{\text{in}}} \times 100\ \%$

Solution:
$$\begin{aligned}E_g &= mgh \\ &= (20.0\ \cancel{\text{kg}})\left(9.8\ \frac{\text{N}}{\cancel{\text{kg}}}\right)(7.5\ \text{m}) \\ &= 1.470 \times 10^3\ \text{J (two extra digits carried)} \\ E_{\text{out}} &= 1.470\ \text{kJ (two extra digits carried)} \\ \text{efficiency} &= \frac{E_{\text{out}}}{E_{\text{in}}} \times 100\ \% \\ &= \frac{1.470\ \cancel{\text{kJ}}}{1.93\ \cancel{\text{kJ}}} \times 100\ \% \\ \text{efficiency} &= 76\ \%\end{aligned}$$

Statement: The efficiency of the rope-and-pulley system is 76 %.

Practice

1. A forklift uses 5200 J of energy to lift a 50.0 kg mass to a height of 4.0 m at a constant speed. What is the efficiency of the forklift? T/I [ans: 38 %]
2. A tow truck attaches a cable to a car stuck in a muddy ditch. The 1250 kg car is pulled up an embankment to a height of 1.8 m at a constant speed. The cable exerts a force of 5500 N over a distance of 12.6 m to pull the car out of the ditch. K/U T/I
   (a) What is the amount of useful energy produced? [ans: 22 kJ]
   (b) What amount of energy is used to pull the car from the ditch? [ans: 69 kJ]
   (c) Calculate the percent efficiency. Why is the efficiency less than 100 %? [ans: 32 %]

Figure 5 Fluorescent lamps are more efficient at producing radiant energy than are incandescent lamps.

Improving the Efficiency of Energy Transformations

Incandescent light bulbs are wasteful because they produce more thermal energy than radiant energy. Light bulbs are more efficient when they transform a greater amount of electrical energy into radiant energy. This is achieved, for example, in fluorescent lamps and compact fluorescent lamps (CFLs).

A CFL is a more compact version of the long fluorescent tube lamps commonly used in large spaces such as office buildings and schools (**Figure 5**). Fluorescent lamps may transform up to 25 % of the supplied electrical energy into radiant energy. This is a significant improvement in efficiency over incandescent light bulbs. Although fluorescent lamps typically cost more than incandescent bulbs to purchase, they may provide the same amount of illumination at a lower overall cost because they use less electrical energy to produce the same amount of radiant energy. However, fluorescent lamps contain mercury, a poisonous element, which may pollute the environment when the lamps are not disposed of properly. **Table 1** describes the energy transformation efficiency of a number of different devices and processes.

Table 1 Energy Transformation Efficiencies of Various Devices and Processes

Device or process	Energy transformation	Major waste output energy	Transformation efficiency	Considerations
gasoline-powered vehicle	chemical (in gasoline) → kinetic (vehicle motion)	thermal	8–15 %	• produces carbon dioxide, which contributes to climate change • creates air pollution
electric vehicle	electrical → kinetic (vehicle motion)	thermal	24–45 %	• currently more expensive to purchase than gasoline-powered vehicles • more efficient than a gasoline vehicle but uses heavy batteries that must be constructed and discarded in special ways to help limit environmental contamination
bicycle	kinetic (pedal) → kinetic (bicycle motion)	thermal	90 %	• most efficient self-powered vehicle • limited to transporting one or two individuals • use is weather dependent • road safety issues
loudspeakers	electrical → sound	thermal	1 %	• efficiency appears to be low, but useful output energy is more than enough to produce audible sound • most of the electrical input is transformed into thermal energy
electric heater	electrical → thermal	radiant	98 %	• very efficient transformer of electrical energy into thermal energy
hydroelectric power plant	kinetic (moving water) → electrical	thermal	80 %	• efficient method of generating electricity • damming rivers may flood land and disrupt ecosystems
nuclear power plant	nuclear → electrical	thermal	30–40 %	• relatively efficient for generating electricity • produces radioactive waste
solar cell	radiant → electrical	thermal	20–40 %	• relatively efficient for generating electricity
photosynthesis	radiant → chemical	thermal	5 %	• although it appears inefficient, it is the only process that transforms radiant energy into chemical energy in organisms • directly or indirectly responsible for maintaining virtually all life on Earth
animal muscles (including human muscles)	chemical (in food) → kinetic (muscle movement)	thermal	20 %	• although it appears to be relatively inefficient, this energy-transforming process provides all the energy animals use to perform work

All the devices and processes in Table 1 transform energy with less than 100 % efficiency. This is a general result: no device or process is 100 % efficient. Another general result is that thermal energy is the most common form of waste energy. Of course, when thermal energy is the desired form of energy output (as in a heater), it is not considered to be waste energy. A primary goal of scientists and engineers is to improve the efficiency of devices and processes that transform energy.

Sources of Energy

We obtain energy from a variety of sources. For example, animals obtain chemical energy from food. This energy originates as radiant energy from the Sun (solar energy), which is captured and transformed into chemical energy by plants in the process of photosynthesis.

Energy-rich substances such as crude oil and natural gas are commonly called **energy resources**. Some energy resources are considered non-renewable, while others are renewable. A **non-renewable energy resource** is an energy-rich substance that cannot be replenished as it is used in energy-transforming processes. Fuels such as coal, oil, and natural gas are common non-renewable energy resources. A **renewable energy resource** is an energy-rich substance with an unlimited supply or a supply that can be replenished as the substance is used in energy-transforming processes. Radiant energy from the Sun is an example of a renewable energy resource.

energy resource energy-rich substance

non-renewable energy resource a substance that cannot be replenished as it is used in energy-transforming processes

renewable energy resource a substance with an unlimited supply or a supply that can be replenished as the substance is used in energy-transforming processes

Non-renewable Energy Resources

Non-renewable energy resources are the most widely used sources of energy. Most automobiles, trains, motorized boats, and airplanes use non-renewable sources of energy. The most common are fossil fuels.

FOSSIL FUELS

Today, most automobile engines use the chemical energy in fuels such as gasoline and diesel. These fuels are called **fossil fuels** because they are the decayed and compressed remains of prehistoric plants and animals that lived between 100 million and 600 million years ago. Like today's plants, ancient plants transformed solar energy into chemical energy through photosynthesis. After the plants died, their bodies decomposed to form chemical mixtures such as crude oil. Today, we pump crude oil from underground deposits and separate, or refine, it into a variety of useful substances, including gasoline and diesel fuels.

fossil fuel fuel produced by the decayed and compressed remains of plants that lived hundreds of millions of years ago

Other commonly used fossil fuels are coal and natural gas. Unlike gasoline and diesel, which are liquids at room temperature, natural gas is a gas that is mainly composed of a compound called methane. Natural gas is used as a fuel in furnaces (for heating), stoves (for cooking), and automobiles (for transportation) (**Figure 6**).

Fossil fuels are non-renewable energy resources because it takes millions of years for them to form. Once we use up the limited supply of these fuels, we will no longer have them as a source of energy. Of course, we will run out of fossil fuels and other non-renewable energy resources faster if we waste them or if we use devices that transform their energy inefficiently.

Figure 6 The burner of a natural gas stove

NUCLEAR ENERGY

Nuclear energy is a form of potential energy produced by interactions in the nucleus of atoms (atomic nuclei). Nuclear energy is released and transformed into other forms of energy when the nuclei of large, unstable atoms such as uranium decompose into smaller, more stable nuclei. Nuclear energy is also released when the nuclei of small atoms such as hydrogen combine to form larger nuclei. The decomposition of large, unstable nuclei is called **nuclear fission**, which takes place in power plants and radioactive elements. The combination of smaller nuclei to form larger nuclei is called **nuclear fusion**, which is the power source of the Sun.

nuclear fission the decomposition of large, unstable nuclei into smaller, more stable nuclei

nuclear fusion a nuclear reaction in which the nuclei of two atoms fuse together to form a larger nucleus

Figure 7 The Pickering Nuclear power plant in Pickering, Ontario

In Canada, nuclear energy is produced mostly by the fission of uranium in large nuclear power plants (**Figure 7**). In this process, nuclear energy is transformed into thermal energy, which heats water and turns it into steam. The high-pressure steam passes through pipes and turns the blades of a turbine, which is connected to an electricity generator (**Figure 8**). The electricity generator produces current electricity that is distributed through a large network of wires called the power grid. Currently, nuclear power plants produce approximately 52 % of Ontario's supply of electrical energy. You will learn more about nuclear energy in Chapter 7.

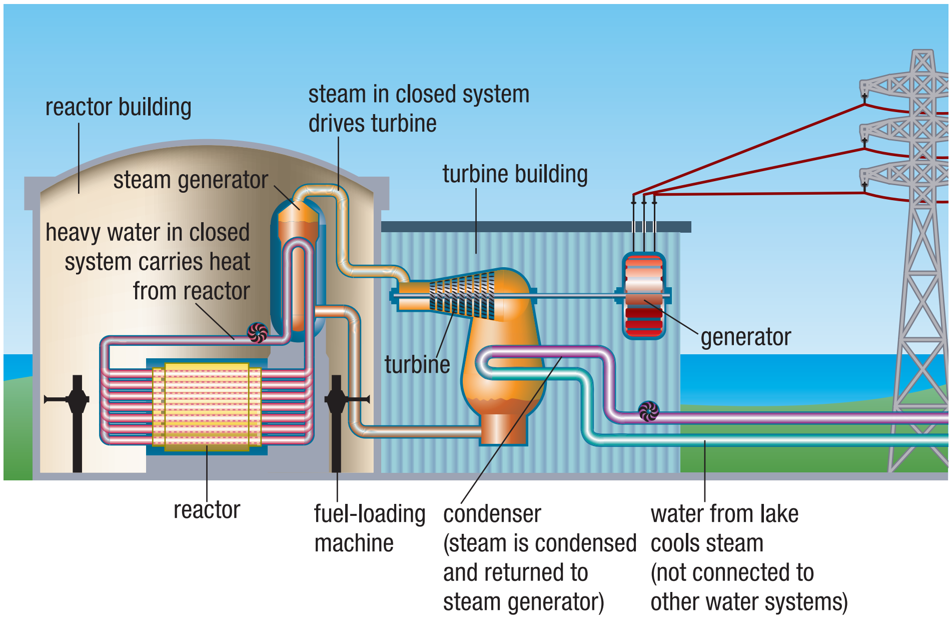

reactor building
steam in closed system drives turbine
steam generator
turbine building
heavy water in closed system carries heat from reactor
turbine
generator
reactor
fuel-loading machine
condenser (steam is condensed and returned to steam generator)
water from lake cools steam (not connected to other water systems)

Figure 8 Basic operations of a nuclear power plant

Renewable Energy Resources

Renewable energy resources are virtually inexhaustible. Some renewable energy resources have been used as sources of energy for a long time, while others have been discovered more recently. The radiant energy of the Sun, the kinetic energy of moving water (waves and waterfalls), and the kinetic energy of moving air (wind) are some of the renewable energy resources that humans have used over time.

SOLAR ENERGY

solar energy radiant energy from the Sun

A common renewable energy resource is radiant energy from the Sun, or **solar energy**. Scientists have estimated that the Sun will continue to emit radiant energy for the next 5 billion years. This is such a long time that we consider the supply of radiant energy to be unlimited and, therefore, renewable.

passive solar design building design that uses the Sun's radiant energy directly for heating

photovoltaic cell a device that transforms radiant energy into electrical energy

Solar energy may be transformed into thermal energy for heating or into electrical energy to run electrical devices and appliances. **Passive solar design** is designing homes and buildings to take direct advantage of the Sun's radiant energy for heating. Alternatively, the Sun's radiant energy may be transformed into electrical energy using a device called a **photovoltaic cell**. The electrical energy produced by photovoltaic cells may be used immediately to run electrical appliances or may be stored in batteries for future use.

Passive Solar Design

In the northern hemisphere, the Sun appears to move from east to west in the southern part of the sky. However, the Sun appears to reach a much higher altitude in the middle of the day during the warmer summer months than it does during the colder winter months. Architects and designers may take advantage of the seasonal changes in the Sun's apparent position in the sky when they design buildings.

For example, they may place windows and eaves on the south-facing side of a building so that the rays of the Sun shine directly through the windows in the winter but not in the summer (**Figure 9**). This design will help the building's interior spaces warm up in the winter and remain cooler in the summer.

Additional passive solar design elements that architects may use include

- orienting buildings so that they have one wall facing the Sun
- placing more windows or larger windows on the sunny side of a building
- placing tall deciduous trees on the sunny side of a building so the Sun's rays are blocked in the summer when the trees are covered in leaves but not in the winter when the leaves have fallen off the trees

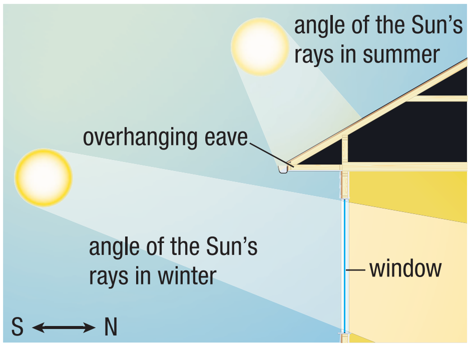

angle of the Sun's rays in summer
overhanging eave
angle of the Sun's rays in winter
window
S ⟷ N

Figure 9 Passive solar design helps reduce the need for furnaces and air conditioners.

Photovoltaic Cells

When solar energy interacts with certain solids, such as modified forms of silicon, the radiant energy may be transformed into electrical energy in the form of an electric current. This is the energy transformation that occurs in a photovoltaic cell. When the source of radiant energy is the Sun, the photovoltaic cell is sometimes called a solar cell (**Figure 10**).

Photovoltaic cells may be placed on the roofs of houses and other buildings or on the surfaces of devices such as outdoor light fixtures and parking meters (**Figure 11**). Since photovoltaic cells rely on a constant supply of solar energy to operate, they are usually connected to batteries, which store excess electrical energy produced on bright, sunny days for use at night or on cloudy days.

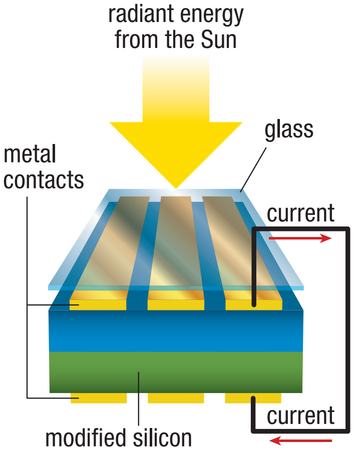


Figure 10 Radiant energy is transformed into electrical energy (electric current) in a photovoltaic cell.

Figure 11 A parking meter uses electrical energy produced by a solar cell.

hydroelectricity electricity produced by transforming the kinetic energy of rushing water into electrical energy

HYDROELECTRICITY

The kinetic energy of rushing water is transformed into electrical energy (electric current) in a hydroelectric power plant. Electrical energy produced in this way is called **hydroelectricity** or, simply, hydro. Hydroelectricity is considered a renewable energy resource because the water cycle ensures that there is always a supply of water with high potential energy in the power plant's reservoir (**Figure 12**). In the water cycle, solar energy causes water in lakes and rivers to evaporate and rise into the upper atmosphere, where the vapour cools, condenses, and falls as precipitation. As water in the reservoir falls through the penstock, it gains kinetic energy and strikes the blades of a fan-like turbine at the lower end. The turbine is connected to an electricity generator, which produces electric current. Hydroelectric power plants produce more electrical energy than any other renewable energy resource in the world.

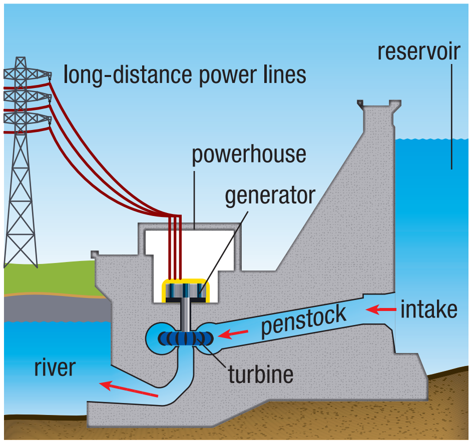


Figure 12 Operations of a typical hydroelectric power plant

A number of other renewable energy resources, in addition to solar energy and hydroelectricity, may help us reduce pollution and meet our energy needs. **Table 2** describes additional renewable energy resources.

LEARNING TIP

"Conserving Energy" and "The Law of Conservation of Energy"
When we say "conserve energy" or "energy conservation," we are referring to ways in which people may avoid wasting energy. However, the law of conservation of energy refers to the idea that the total amount of energy is conserved when one form of energy is transformed into another form of energy.

Table 2 Additional Renewable Energy Resources

Renewable energy resource	Description	Considerations
geothermal	• Earth possesses a virtually unlimited supply of thermal energy deep underground. • Geothermal energy may be used directly for heating and cooling or be transformed into electrical energy.	• accessible only in certain areas • in some locations, deep holes need to be drilled into the ground to reach pockets of thermal energy
wind	• Wind strikes the blades of a fan-like turbine, which turns an electricity generator that generates electrical energy.	• can be used only in windy locations • turbines generate electricity only when wind is blowing • turbines are noisy, and the blades may strike birds and other wildlife
tidal	• As tides rise and fall, the moving water strikes the blades of a turbine, which turns a generator. The generator generates electrical energy. • Tidal turbines are similar to wind turbines and are placed in bodies of water where significant tidal movements occur.	• turbines only work during tidal movements • may disrupt aquatic ecosystems
biofuels	• Biofuels are solid, liquid, and gaseous fuels derived from the bodies of living or dead plants and animals. • Biofuels can include wood, biological waste, and gases such as methane produced during the decomposition of plant matter. • Solid biofuel may be called biomass and gaseous biofuel may be called biogas.	• burning the fuels may produce air pollutants, including carbon dioxide, which is linked to climate change

CAREER LINK

To learn more about becoming an energy operations manager or power systems engineer,

GO TO NELSON SCIENCE

Although renewable energy resources are replaceable or unlimited in supply, non-renewable energy resources such as coal, oil, and natural gas continue to be the most widely used sources of energy in the world today. Much of this is because most of today's electric power plants, engines, heating systems, and appliances are designed to transform the chemical energy in fossil fuels into other forms of energy. The large-scale, global use of fossil fuels and fossil fuel–using devices keeps prices relatively low.

Conserving Energy

Energy may be conserved by designing, producing, and using machines, appliances, and devices that transform energy more efficiently. Energy may also be conserved by

- turning lights off when not required
- switching off electrical devices instead of leaving them on standby mode
- taking short showers instead of baths if possible
- running dishwashers and clothes washers only when they are full
- hanging clothes to dry
- using fans to reduce the need for air conditioning
- using public transit and carpooling when possible

WEB LINK

To learn more about ways you can conserve energy,

GO TO NELSON SCIENCE

5.4 Summary

- The equation to calculate the efficiency of an energy transformation is $\text{efficiency} = \frac{E_{\text{out}}}{E_{\text{in}}} \times 100\ \%$, where E_{out} is the useful energy output and E_{in} is the energy input.
- No energy-transforming device is 100 % efficient. Typically the waste energy is in the form of thermal energy.
- Non-renewable energy resources are energy-rich substances that cannot be replenished when they are used up in the energy transformation process.
- Renewable energy resources are energy-rich substances with an unlimited supply or a supply that can be replenished.
- There are many ways to conserve energy.

UNIT TASK BOOKMARK

You can apply what you have learned about efficiency and energy resources to the Unit Task on p. 360.

5.4 Questions

1. In a race, a 54 kg athlete runs from rest to a speed of 11 m/s on a flat surface. The athlete's body has an efficiency of 85 % during the run. How much input energy did the athlete provide? T/I
2. Athletes who compete in downhill skiing try to lose as little energy as possible. A skier starts from rest at the top of a 65 m hill and skis to the bottom as fast as possible. When she arrives at the bottom, she has a speed of 23 m/s. T/I
   (a) Calculate the efficiency of the skier.
   (b) Explain why the mass of the skier is not required when calculating the efficiency.
3. A golf club with 65 J of kinetic energy strikes a stationary golf ball with a mass of 46 g. The energy transfer is only 20 % efficient. Calculate the initial speed of the golf ball. T/I
4. Describe one advantage and one disadvantage in using
   (a) non-renewable energy resources
   (b) renewable energy resources K/U A
5. Compare nuclear power plants with hydroelectric power plants in terms of efficiency, method of generating electricity, energy transformations, and environmental impact. K/U C A
6. An article on the Internet claims, "Fossil fuels are actually a renewable energy resource since decaying plant and animal matter is making new oil, natural gas, and coal all the time." Discuss the validity of this statement. C A
7. In this section, two different methods of using solar energy were described: passive solar design and photovoltaic cells. Explain the difference between passive solar design and photovoltaic cells. K/U

5.5 Power

It takes time to change one form of energy into another. The rate at which energy is transformed depends on certain factors. For example, your muscles transform the chemical energy in food into kinetic energy (motion) and thermal energy much faster if you run up a set of stairs than if you walk slowly up the same set of stairs. Your body feels warmer and more tired the faster you climb the stairs.

You may also analyze this situation in terms of the work your body does in climbing to the top of the stairs. Whether you run or walk up a set of stairs, your body applies the same force against gravity and travels the same vertical distance. Your body does the same amount of work in each case. However, your body does the work faster when you run and slower when you walk. In other words, the rate at which work is done depends on how fast you move.

power (*P*) the rate of transforming energy or doing work

LEARNING **TIP**

Power and the Work–Energy Principle

Although we developed the work–energy principle ($W_{\text{net}} = \Delta E$) in terms of changes in an object's kinetic energy, the principle also applies when an object's potential energy changes.

Physicists use the word **power (*P*)** to describe the rate at which energy is transformed, or the rate at which work is done. Your body produces more power when you run up a set of stairs than when you climb up slowly. We may describe power mathematically as follows:

$$P = \frac{\Delta E}{\Delta t} \quad \text{or} \quad P = \frac{W_{\text{net}}}{\Delta t}$$

Energy, work, and time are scalar quantities, so power is also a scalar quantity (it has no direction associated with it). Since energy and work are measured in joules and time is measured in seconds, power is measured in joules per second (J/s). In the SI system, the unit for power is called the watt (W) in honour of James Watt, a Scottish engineer who invented the first practical steam engine. One watt is equal to 1 J/s.

Earlier in this chapter, you learned that work involves the transfer, or transformation, of energy. For example, if a golf club does 100 J of work on a golf ball in 0.1 s, then the club transfers 100 J of energy to the golf ball in 0.1 s. The golf ball's energy changes by 100 J in 0.1 s. Thus, the work done by the club on the golf ball is equal to the change in energy, or $W_{\text{net}} = \Delta E$. We may calculate the golf club's power using the equation $P = \frac{W_{\text{net}}}{\Delta t}$ or the equation $P = \frac{\Delta E}{\Delta t}$. Both equations yield the same result because $W_{\text{net}} = \Delta E$. In Tutorial 1, you will solve problems involving power.

Investigation **5.5.1**

Student Power (p. 258)

In this investigation, you will explore your own personal power and work done using different types of fitness equipment. You will design your own procedure using fitness equipment of your choice.

Tutorial 1 Calculating Power

In this Tutorial, we will use the equation $P = \frac{\Delta E}{\Delta t}$ to solve both of the following Sample Problems, although we may use the equation $P = \frac{W_{\text{net}}}{\Delta t}$ as well since $W_{\text{net}} = \Delta E$.

Sample Problem 1

How much power does a swimmer produce if she transforms 2.4 kJ of chemical energy (in food) into kinetic energy and thermal energy in 12.5 s?

Solution

Since this question gives the values for the energy transformation and the time interval, we may use the equation $P = \frac{\Delta E}{\Delta t}$ to calculate the power.

Given: $\Delta E = 2.4$ kJ or 2.4×10^3 J; $\Delta t = 12.5$ s

Required: P

Analysis: $P = \frac{\Delta E}{\Delta t}$

Solution: $P = \frac{\Delta E}{\Delta t}$

$$= \frac{2.4 \times 10^3\ \text{J}}{12.5\ \text{s}}$$

$$= 190\ \text{J/s}$$

$$P = 190\ \text{W}$$

Statement: The swimmer's power is 190 W.

Sample Problem 2

A 64 kg student climbs from the ground floor to the second floor of his school in 5.5 s. The second floor is 3.7 m above the ground floor. What is the student's power?

Solution

The first two phrases in this problem describe a situation in which a student travels from a lower floor to a higher floor of his school. This means that the student's gravitational potential energy increases from a value of zero at the ground floor (the reference level) to a value given by the equation $E_g = mgh$ at the second floor. Thus, the value of E_g is equal to the change in the student's energy, ΔE, which may be substituted into the equation $P = \frac{\Delta E}{\Delta t}$ to calculate the student's power.

Given: $m = 64$ kg; $g = 9.8$ N/kg; $h = 3.7$ m; $\Delta t = 5.5$ s

Required: P

Analysis: $E_g = mgh$; $P = \frac{\Delta E}{\Delta t}$

Solution: $E_g = mgh$

$$= (64\ \cancel{\text{kg}})\left(9.8\ \frac{\text{N}}{\cancel{\text{kg}}}\right)(3.7\ \text{m})$$

$$E_g = 2.321 \times 10^3\ \text{J (two extra digits carried)}$$

$$\Delta E = 2.321 \times 10^3\ \text{J}$$

$$P = \frac{\Delta E}{\Delta t}$$

$$= \frac{2.321 \times 10^3\ \text{J}}{5.5\ \text{s}}$$

$$= 4.2 \times 10^2\ \text{J/s}$$

$$P = 4.2 \times 10^2\ \text{W}$$

Statement: The student's power is 4.2×10^2 W.

Practice

1. How long would it take a motor with 0.50 kW of power to do 1200 J of work? T/I [ans: 2.4 s]
2. A mountain climber with a mass of 55 kg starts from a height of 850 m above sea level at 9 in the morning and reaches a height of 2400 m by noon. What is the climber's average power? T/I [ans: 77 W]
3. A 60.0 kg person accelerates from rest to 12 m/s in 6.0 s. What is the person's power? T/I [ans: 720 W]

Mini **Investigation**

Human Power

Skills: Performing, Observing, Analyzing

SKILLS HANDBOOK **A6.2**

In this activity, you will compare the power of a student walking slowly and walking quickly up a flight of stairs.

Equipment and Materials: bathroom scale; metric tape measure or metre stick; staircase; stopwatch

1. Use a scale to measure your partner's mass. Calculate your partner's weight in newtons.
2. Use a tape measure or metre stick to measure the height of a staircase. You may do this by measuring the height of one step and multiplying this by the total number of steps.
3. Use a stopwatch to measure the time it takes your partner to walk up the stairs slowly at constant speed. Repeat this three times and average the results.

Exercise caution when walking up the stairs. Never run.

4. Measure the time it takes your partner to walk up the stairs more quickly at constant speed. Repeat this three times and average the results.

A. Calculate the average power produced by walking up the stairs slowly. T/I

B. Calculate the average power produced by walking up the stairs more quickly. T/I

C. Was your partner's power greater when walking up the stairs quickly or slowly? Explain your observations. T/I

D. Compare your partner's power in walking up the stairs slowly and walking up the stairs quickly to the power of a 100 W light bulb. Which process produces the most power: walking up the stairs slowly, walking up the stairs more quickly, or using the light bulb? Explain why you think this is the case. T/I

Electrical Power

Electrical devices transform electrical energy into other forms of energy. For example, the hot, glowing elements of a toaster transform electrical energy into thermal energy and radiant energy, and an electric guitar transforms electrical energy into sound energy and thermal energy (**Figure 1**).

Like other energy-transforming devices, electrical devices may transform energy quickly or slowly. When they transform energy more quickly, they are more powerful, and when they transform energy more slowly, they are less powerful. The maximum power of an electrical device or appliance is sometimes referred to as the device's power rating. The power rating of an electrical device may be calculated using the equation $P = \frac{\Delta E}{\Delta t}$. Rearranging this equation yields the equation $\Delta E = P\Delta t$, which may be used to calculate the amount of energy transformed by a device. In the following Tutorial, you will calculate the power of an electrical device.

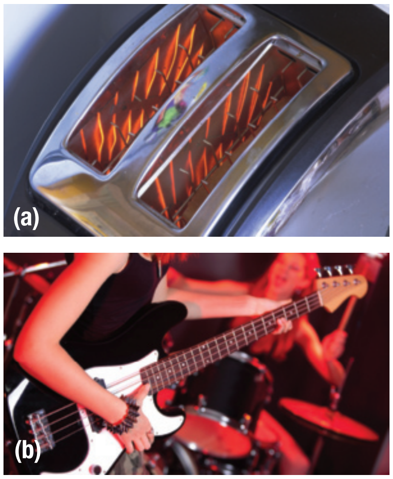


Figure 1 (a) A toaster and (b) an electric guitar transform electrical energy.

Tutorial 2 Calculating the Power of an Electrical Device

In this Tutorial, we will determine the power of an electrical device.

Sample Problem 1

What is the power of an electric elevator motor if it uses 2.9×10^5 J of electrical energy to lift an elevator car 12 m in 16 s?

Solution

In this problem, the elevator motor transforms 2.9×10^5 J of electrical energy into the elevator car's gravitational potential energy when it is 12 m above the ground. Therefore, $\Delta E = 2.9 \times 10^5$ J and $\Delta t = 16$ s.

Given: $\Delta E = 2.9 \times 10^5$ J; $\Delta t = 16$ s

Required: P

Analysis: $P = \frac{\Delta E}{\Delta t}$

Solution:

$$\begin{aligned} P &= \frac{\Delta E}{\Delta t} \\ &= \frac{2.9 \times 10^5 \text{ J}}{16 \text{ s}} \\ &= 1.8 \times 10^4 \text{ J/s} \\ &= 1.8 \times 10^4 \text{ W} \\ P &= 18 \text{ kW} \end{aligned}$$

Statement: The elevator motor's power is 18 kW.

Practice

1. The Pickering Nuclear power plant has a power rating of 3100 MW. How much energy can the generating station produce in one day? (Answer in MJ.) T/I [ans: 2.7×10^8 MJ]

Table 1 Power Ratings of Appliances

Appliance	Power rating (W)
laptop computer	20–75
vacuum cleaner	200–700
microwave oven	600–1500
dishwasher	1200–1500
refrigerator	100–500
stove	6000–10 000

The electric elevator motor in Tutorial 2 transformed 290 kJ of electrical energy into gravitational potential energy in 16 s—a power of 18 kW. This is a common result for the power ratings of electrical devices: the ratings tend to be in the hundreds or thousands of watts. **Table 1** lists the power ratings of some typical household appliances.

Energy Ratings and the Cost of Electricity

Companies that provide electrical energy to consumers use electricity meters to measure the total amount of electrical energy used (**Figure 2** on the next page). This amount depends on the number of electrical devices being used, the power rating of each device, and the total amount of time each device is used. It is common for electricity meters to measure the electrical energy used in units of kilowatt hours (kWh).

The use of the kilowatt hour for measuring a change in energy (energy used) becomes apparent when we analyze the equation $\Delta E = P\Delta t$. When power, P, is measured in kilowatts, kW, and the time interval, Δt, is measured in hours, h, the product $P\Delta t$ produces the unit kilowatt hours, kWh. The energy used (transformed) by an electrical appliance, ΔE, is sometimes called the energy consumption rating, or energy rating, of the appliance. Thus, the energy rating is commonly measured in kilowatt hours. In the following Tutorial, we will determine the energy rating of a common household appliance and the cost of operating the appliance.

Figure 2 Electricity meters measure the amount of electrical energy used.

Tutorial 3 Determining the Energy Rating of a Device

In this Tutorial, we will use the equation $P = \frac{\Delta E}{\Delta t}$ to calculate the energy rating and the cost of operating an electrical device with a particular power rating for a given amount of time.

Sample Problem 1

What is the cost of operating a 25 W light bulb 4.0 h a day for 6.0 days if the price of electrical energy is 5¢/kWh?

Solution

We will solve this problem in two parts. In part (a), we will calculate the amount of energy the light bulb will use (transform) in 6 days of operation (4 h per day). Then, in part (b), we will use the amount of electrical energy transformed to calculate the cost of the electrical energy. Note that the amount of electrical energy transformed must be calculated in kilowatt hours, not joules, since the electricity provider charges per kilowatt hour, not per joule. Therefore, we convert the units first.

Given: $P = 25$ W or 0.025 kW; $\Delta t = 6.0\ \cancel{\text{d}}\left(\frac{4.0\ \text{h}}{\cancel{\text{d}}}\right) = 24$ h; price of electrical energy = 5¢/kWh

Required: ΔE, energy used (transformed); cost

Analysis: $P = \frac{\Delta E}{\Delta t}$

Solution:

(a)
$$P = \frac{\Delta E}{\Delta t}$$
$$\Delta E = P\Delta t$$
$$= (0.025\ \text{kW})(24\ \text{h})$$
$$\Delta E = 0.60\ \text{kWh}$$

(b)
$$\text{cost} = (0.60\ \cancel{\text{kWh}})\left(\frac{5¢}{\cancel{\text{kWh}}}\right)$$
$$\text{cost} = 3¢$$

Statement: It costs 3¢ to operate a 25 W light bulb for 24 h.

Practice

1. Twenty incandescent light bulbs are turned on for 12 h a day for an entire year to light up a store. Each bulb has a power rating of 100.0 W. The average cost of electricity is 6.0¢/kWh. T/I
   - (a) Determine the total amount of energy used by all the bulbs in the year. [ans: 8800 kWh]
   - (b) Calculate the cost of lighting the store for the year. [ans: $530]
   - (c) How much money could be saved by using CFLs instead of the incandescent bulbs if each CFL has a power rating of 23 W? [ans: $400]

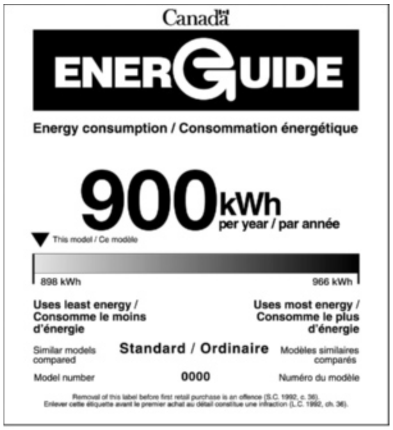

Canada
ENERGUIDE
Energy consumption / Consommation énergétique
900 kWh
per year / par année
This model / Ce modèle
898 kWh
966 kWh
Uses least energy / Consomme le moins d'énergie
Uses most energy / Consomme le plus d'énergie
Similar models compared
Standard / Ordinaire
Modèles similaires comparés
Model number
0000
Numéro du modèle

Figure 3 EnerGuide label on a typical household refrigerator

The Canadian government requires all manufacturers of electrical appliances to place an EnerGuide label on all electrical appliances sold in Canada (**Figure 3**). The EnerGuide label shows the annual energy rating for an appliance in kilowatt hours. The consumer may use this value and the price of electrical energy to determine the average annual cost of operating the appliance. Consumers are encouraged to purchase appliances that have the lowest energy consumption rating possible. This will allow them to consume less electrical energy and save money.

5.5 Summary

- Power is the rate of transforming energy or the rate of doing work. The equations for power are $P = \frac{W_{\text{net}}}{\Delta t}$ or $P = \frac{\Delta E}{\Delta t}$.
- Power is a scalar quantity measured in watts (1 W = 1 J/s).
- Electrical devices transform electrical energy into other forms of energy, and the power rating of these devices can be determined using the equations for power.
- The electrical energy used by an electrical device can be found using the equation $\Delta E = P\Delta t$.

5.5 Questions

1. A 54 kg person climbs a set of stairs at a constant speed from the first floor to the fourth floor in 32 s. The change in height from one floor to the next is 3.4 m. T/I
   (a) Calculate the gravitational potential energy at the top of the climb relative to the first floor.
   (b) Calculate the power of the person for the climb.
   (c) If a lighter person climbed the stairs in the same time, would this person's power be higher or lower? Explain.
2. A 65 kg student climbs 5.0 m up a rope in gym class at a constant speed of 1.4 m/s. T/I
   (a) Determine the time it takes the student to climb up the rope, and then determine the student's power.
   (b) Determine the student's power without finding the time it takes the student to climb up the rope. Explain your reasoning.
3. A student uses a pulley to lift a mass into the air. K/U C
   (a) Assume the mass is lifted at a constant speed. Describe one way you could determine the power of the student when she is lifting the mass.
   (b) Assume the mass started from rest at ground level and accelerated upward with a constant acceleration. What types of energy will the object have while it is being pulled up by the student? How would you determine the student's power in this case?
4. A family of five is planning to install solar panels on the roof of their home to help reduce the cost of electricity and save energy to help the environment. The family plans to install 10 panels, each with a power rating of 600 W. On average, a solar panel can produce electricity for 4.5 h daily. T/I
   (a) How much solar energy will the solar panels transform into electrical energy each day?
   (b) Assume the average cost of electricity is 5.5¢/kWh. How much money will the family save in a year on their electrical energy bill?
   (c) Each person in the family uses electrical energy at an average rate of 2 kWh per day. Will they still need to buy electricity from an electrical energy supplier? Explain your reasoning.
5. Show that 1 kWh = 3.6 MJ. C

5.6 Explore Applications of Renewable Energy Sources

Going Off the Grid

SKILLS MENU

- Researching
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating
- Identifying Alternatives

Families and individuals are becoming more concerned with the rising cost of energy and the use of energy resources that harm the environment. More and more Canadians are considering alternative sources of energy. **Brownouts**, which are short-term reductions in the supply of electricity, are becoming more common in the summer. When the demand for electricity peaks, power companies are unable to keep up with the demand. Governments are planning to construct new nuclear power plants to meet the rising demand for electricity.

Most buildings in Canada are connected to a large electricity distribution system called the **electrical power grid**. These grids are managed by large utility companies. Most families rely on these networks to supply their electrical energy needs. They may not be aware of alternative sources of energy.

brownout reduced supply of electricity caused by system damage or excess demand

electrical power grid a large electricity distribution system composed of a network of electrical power plants and electricity distribution towers and cables

The Application

David Jamal, a Grade 11 student, lives with his mother, father, brother, and two sisters in a mid-sized, detached, suburban home on the outskirts of Sudbury, Ontario (**Figure 1**). The Jamals have been discussing their family's energy consumption and have made several changes to reduce energy use as much as possible. Some of the changes are the installation of a programmable thermostat, a drain water heat-recovery system, ceiling fans, and CFLs (**Figure 2**). The ceiling fans help keep rooms cool during warm summer nights. In the winter, the programmable thermostat turns the furnace down when everyone is out and back up again just before everyone gets home.

These devices have reduced the Jamals' heating and air conditioning costs quite a bit, but their monthly electricity bills are still very high. The cost of electricity also seems to increase every year. The family has decided to try a bigger change—they are going to reduce their reliance on the power grid by generating their own electricity!

Figure 1 The Jamal family's home

Figure 2 Ceiling fan with CFLs

After learning about renewable energy resources such as solar energy, wind energy, and geothermal energy at school and on the Internet, David convinced his parents to speak to a renewable energy consultant and explore the possibility of installing solar panels on the roof of their home or a wind turbine in their backyard, or both. David's parents have agreed with this idea and have decided to look into the matter further.

You and your group members will assume the role of renewable energy consultants. You have been hired to advise the Jamal family of its renewable energy options. You will take into consideration the Jamal family's situation and the location of their home. You will explain how residential photovoltaic and wind turbine systems work and how they can be installed in homes like the Jamals'. You will also advise the Jamals of costs associated with installing solar panels and wind turbines. Finally, you will identify government programs that provide incentives to residents who install renewable energy systems.

CAREER LINK

To learn more about becoming a renewable energy consultant or sustainable energy researcher,

GO TO NELSON SCIENCE

Your Goal

To advise the Jamal family on how they may generate their own electricity from a renewable energy source

WEB LINK

To learn more about renewable energy sources and off-the-grid energy generation,

GO TO NELSON SCIENCE

Research

Conduct library or Internet research about renewable energy sources and off-the-grid electrical energy generation, especially through the use of solar panels and wind turbines. Be sure to research the costs associated with each method of generating energy.

Summarize

Use the following questions to summarize your recommendations to the Jamal family:

- What are some of the benefits and drawbacks of the Jamals' current energy systems? What are some of the benefits and drawbacks of generating their own electricity?
- How do residential photovoltaic and wind turbine systems work?
- What do the Jamals have to do to start generating their own electricity?
- Which renewable energy-generating systems would be the most cost-effective for the Jamals to implement in their home, taking into consideration the costs associated with installation and maintenance?
- How much could the family reduce their electricity bills by generating their own electricity?

UNIT TASK BOOKMARK

You can apply what you have learned about renewable energy sources to the Unit Task on page 360.

Communicate

Give your renewable energy consulting firm a name and present your advice to the Jamal family in the form of a renewable energy plan. You may present the plan verbally, in writing, or in the form of a multimedia presentation to the class or a smaller group of your classmates.

Plan for Action

Plan a media campaign you may use to inform students and the residents in your school community of off-the-grid electrical energy generation and other renewable energy options. Compare these renewable energy sources to non-renewable sources used in Ontario (fossil fuels, for example). Be sure to research the affordability of each option and inform your audience of the most cost-effective choices. You may prepare sample community or school newspaper articles, posters, pamphlets, T-shirt logos, or radio and TV announcements to share your findings with your school community.

GO TO NELSON SCIENCE

CHAPTER 5 Investigations

Investigation 5.2.1 CONTROLLED EXPERIMENT

Conservation of Energy

In this investigation, you will explore what happens to the gravitational potential energy, kinetic energy, and total mechanical energy of a cart as it rolls down a ramp.

Testable Question

What are the relationships between

- gravitational potential energy and position
- kinetic energy and position
- total mechanical energy and position

for a laboratory cart rolling down a ramp?

Hypothesis/Prediction

Make hypotheses based on the Testable Question. Your hypotheses should include predictions and reasons for your predictions.

Variables

Read the Testable Question, Experimental Design, and Procedure, and identify the manipulated variables, responding variables, and controlled variables in this experiment.

Experimental Design

In this experiment, you will place a motion sensor at the top of a ramp and use the sensor's software to sketch a position–time graph of a laboratory cart as it rolls down the ramp. You will use one position near the end of the relevant data as the final position or reference point. You will use other positions to find the height and speed of the cart. You will then use these data to calculate the gravitational potential energy, kinetic energy, and total mechanical energy of the cart. Finally, you will look for patterns in these data to complete the experiment.

Equipment and Materials

- eye protection
- ramp
- 3–4 textbooks or wood blocks
- metre stick
- motion sensor
- laboratory cart

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Procedure

SKILLS HANDBOOK A2.2

1. Prop up one end of a ramp using textbooks or wood blocks. Use a metre stick to measure the length of the ramp (*L*) and the height of the ramp (*H*) as shown in **Figure 1**.
2. Place the motion sensor at the top of the ramp, directed toward the bottom. Release the cart from a position near the motion sensor. Obtain the position–time graph of the cart as it rolls down the ramp away from the motion sensor.
3. Choose one point on the position–time graph near the end of the run. The position coordinate for this point will represent the final position $\vec{d}_2$ and the reference point that will be used to determine the height of the cart ($h = 0$ at the reference point). This point will not change throughout the experiment.
4. To find the height of any other position above the reference point, examine Figure 1. The ramp itself forms a larger triangle and the displacement of the cart down the ramp forms a smaller, similar triangle. Using these similar triangles, we have

$$\frac{h}{\Delta d} = \frac{H}{L}$$

$$h = \Delta d\left(\frac{H}{L}\right)$$

This equation will be used to calculate the height, *h*, of the cart on the ramp.

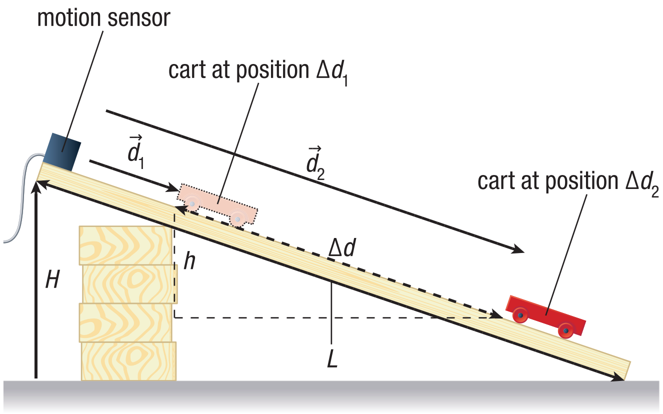


Figure 1

5. To determine the speed at any point on the position–time graph, use the slope tool in the program for the motion sensor.

6. Starting with a point near the start of the run, determine the position, $\vec{d}_1$, and the speed, v, at this point. Use these values to complete the first row of **Table 1**.

7. Use other positions from the graph to complete the next three rows in Table 1. These positions should get gradually closer to the final position.

Table 1 Data for Conservation of Energy Investigation

Initial position	Variable							
	$\vec{d}_2$	$\vec{d}_1$	$\Delta d = \vec{d}_2 - \vec{d}_1$	h	v	E_g	E_k	E_m
1								
2								
3								
4								

Analyze and Evaluate

(a) What variables were measured and manipulated in this investigation? What relationships, based on the Testable Question, were tested?

(b) Calculate the cart's gravitational potential energy, E_g, kinetic energy, E_k, and total mechanical energy, E_m, for each initial position in Table 1. T/I

(c) Answer the Testable Question. T/I

(d) What effect does friction have on the different types of energy in this experiment? Use an FBD and the concept of work to explain your reasoning. T/I C

(e) What are some possible sources of error? T/I

(f) Evaluate your hypotheses. How did your hypotheses compare to the results of the experiment? T/I

(g) What energy changes take place in this experiment? What evidence have you found that almost no energy is lost in this experiment? T/I

(h) Why is it essential to keep the final position, $\vec{d}_2$, fixed for the entire investigation when testing conservation of energy? T/I

(i) In your own words, explain how to determine the height of the cart above the final position using the position–time graph. T/I C

Apply and Extend

(j) Imagine doing the experiment again with one change: starting the cart at the bottom and launching it up the sensor. You may assume the cart does not hit the sensor. How would the initial speed up the ramp compare to the final speed down the ramp at the same position? Explain your reasoning. T/I

Investigation 5.5.1 OBSERVATIONAL STUDY

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Student Power

In this investigation, you will explore your own personal power using different types of fitness equipment. To calculate your power, you will first determine how much work you have done while performing different exercises.

You must measure your own work and power while performing exercises for brief and long periods of time. The brief activity can last for 10 s and the long activity will last for 2 min. The activities should involve two types of fitness equipment—one that uses mainly arm muscles and another that uses mainly leg muscles. Keep safety in mind when selecting exercises. Perform exercises at a comfortable level rather than pushing yourself to find maximum power.

You should never use any fitness equipment without being instructed on how to use it safely. Always get your teacher's approval before using any equipment. Notify your teacher of any health problems that may prevent you from completing this activity safely. Be careful when lifting weights and avoid fast movements.

Purpose

To determine how the power of your legs compares to the power of your arms for different exercises, and to observe how the amount of work changes as the duration of an exercise increases

Equipment and Materials

- fitness equipment
- stopwatch
- metre stick
- bathroom scale

Procedure

SKILLS HANDBOOK A2.4

1. Choose a piece of fitness equipment that can be used to exercise your arms. The exercise you perform should involve lifting weights.
2. Prepare a table in your notebook similar to **Table 1** below. Record the mass you will be lifting in the table. To calculate the force, use the equation $F_g = mg$.
3. Before performing the activity, measure the distance for the motion of your arms when lifting the mass once. The long exercise might involve lifting a lighter mass, but it should be the same exercise.
4. Complete each exercise, recording any necessary information. Calculate the total work done by multiplying the force by the distance and the number of repetitions. Use the work and time to calculate the power. Make sure you take a break after each activity. You can accomplish this by alternating turns among group members.
5. Choose a piece of fitness equipment you can use to exercise your legs. Your exercise should involve lifting weights with your legs. The weight could be external, such as in a leg press, or even your own body if you are using a stair climber.
6. Repeat Step 3 using the new piece of equipment (using your legs instead of your arms).
7. Complete each exercise, recording any necessary information. Calculate the total work done by multiplying the force by the distance and the number of repetitions. Use the work and time to calculate the power. Make sure you take a break after each activity.

Analyze and Evaluate

(a) How does the amount of work done by your arms in the brief exercises compare with the work done in the long exercises? How does the power compare under the same circumstances? Explain why the powers are different. T/I

(b) How does the amount of work done by your legs in the brief exercises compare with the work done in the long exercises? How does the power compare under the same circumstances? Explain why the powers are different. T/I

(c) How does the power of your legs compare to the power of your arms? Explain why they are different. T/I

Apply and Extend

(d) People often find that a workout gets easier over time. Describe two changes that can be made to increase the work done and the power required for each exercise to make it more challenging. T/I A

(e) Many strength-training exercises are brief, while cardiorespiratory exercises take much longer. Use what you have learned in this activity to explain why this is true. C A

(f) Explain why both the work done and the power are important things to consider when designing a new workout routine. T/I A

Table 1 Observations

Type of exercise	Mass (kg)	Force (N)	Distance (m)	Number of repetitions	Time (s)	Work (J)	Power (W)
arms (brief)							
arms (long)							
legs (brief)							
legs (long)							

CHAPTER 5 SUMMARY

Summary Questions

1. Create a study guide based on the Key Concepts on page 220. For each point, create three or four subpoints that provide further information, relevant examples, explanatory diagrams, or general equations.
2. Look back at the Starting Points questions on page 220. Answer these questions using what you have learned in this chapter. Compare your latest answers to those that you wrote at the beginning of the chapter. Note how your answers have changed.

Vocabulary

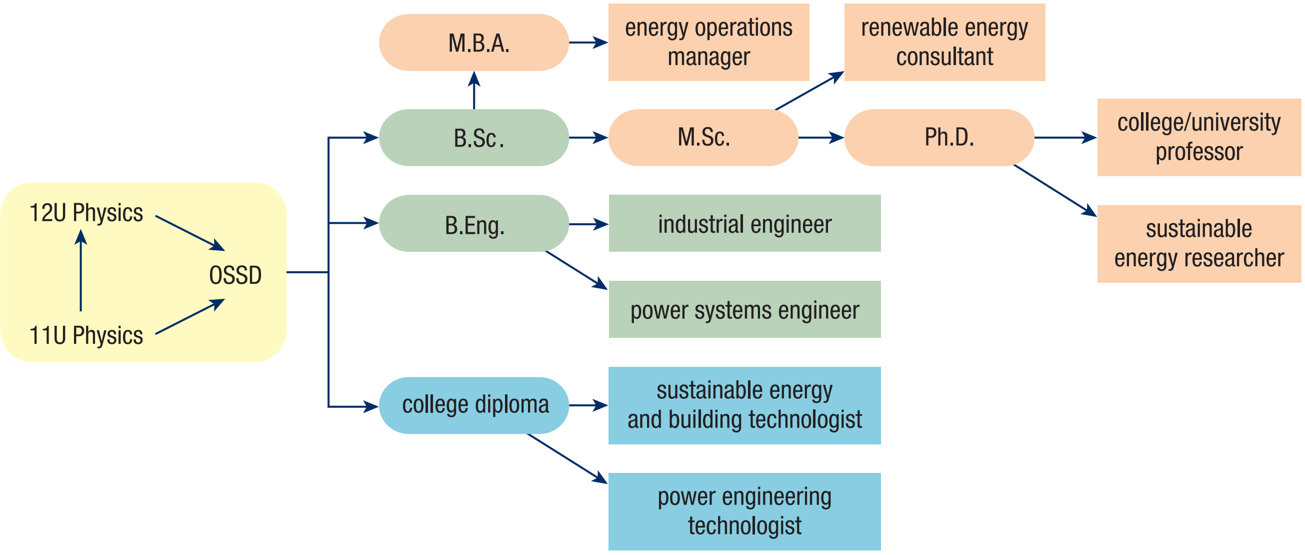
mechanical work (W) (p. 222)
energy (p. 230)
kinetic energy (E_k) (p. 230)
work–energy principle (p. 232)
potential energy (p. 233)
gravitational potential energy (p. 233)
reference level (p. 233)
mechanical energy (p. 235)
thermal energy (p. 236)
nuclear energy (p. 237)
energy transformation (p. 237)
law of conservation of energy (p. 238)
efficiency (p. 242)
energy resource (p. 245)
non-renewable energy resource (p. 245)
renewable energy resource (p. 245)
fossil fuel (p. 245)
nuclear fission (p. 245)
nuclear fusion (p. 245)
solar energy (p. 246)
passive solar design (p. 246)
photovoltaic cell (p. 246)
hydroelectricity (p. 247)
power (P) (p. 250)
brownout (p. 255)
electrical power grid (p. 255)

CAREER PATHWAYS

SKILLS HANDBOOK A7

Grade 11 Physics can lead to a wide range of careers. Some require a college diploma or a B.Sc. degree. Others require specialized or postgraduate degrees. This graphic organizer shows a few pathways to careers related to topics covered in this chapter.

1. Select an interesting career that relates to Work, Energy, Power, and Society. Research the educational pathway you would need to follow to pursue this career.
2. What is involved in becoming an energy consultant? Research at least two pathways that could lead to this career, and prepare a brief report of your findings.



M.B.A.
energy operations manager
renewable energy consultant
B.Sc.
M.Sc.
Ph.D.
college/university professor
12U Physics
OSSD
11U Physics
B.Eng.
industrial engineer
sustainable energy researcher
power systems engineer
college diploma
sustainable energy and building technologist
power engineering technologist

GO TO NELSON SCIENCE

CHAPTER 5 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. The SI unit for work is the joule. What is one joule equivalent to in SI units? (5.1) K/U
   (a) $1\ \text{m/s}^2$
   (b) $1\ \text{N}\cdot\text{m}$
   (c) $1\dfrac{\text{kg}\cdot\text{m}}{\text{s}^2}$
   (d) $1\dfrac{\text{kg}}{\text{m}\cdot\text{s}^2}$
2. A farmer lifts a 216 N bale of hay onto the bed of a wagon that is 2.00 m above the ground. How much work is done on the bale of hay? (5.1) T/I
   (a) 132 J
   (b) 232 J
   (c) 432 J
   (d) 832 J
3. What is the kinetic energy of a 2.0×10^3 kg car travelling at a speed of 20.0 m/s? (5.2) T/I
   (a) 2.0×10^5 J
   (b) 4.0×10^5 J
   (c) 4.0×10^6 J
   (d) 8.0×10^6 J
4. A physics book is sitting on an overhead shelf and a biology book is sitting on a table at waist level. The books are equal in mass. Which of the following statements about this situation is correct? (5.2) K/U
   (a) The physics book has less potential energy than the biology book.
   (b) The physics book has more potential energy than the biology book.
   (c) The physics book has more kinetic energy than the biology book.
   (d) Both books have the same amount of kinetic energy and potential energy.
5. What is the basis of thermal energy? (5.3) K/U
   (a) the random motion of atoms and molecules
   (b) the accumulation of static charges on a surface
   (c) the interaction of protons and neutrons in atoms
   (d) the stretching and twisting of molecules
6. An apple hanging from a tree has no initial kinetic energy (E_{k_i}) and a certain amount of initial potential energy (E_{g_i}). The stem of the apple breaks, and the apple falls to the ground. When the apple has fallen halfway to the ground, how do its final kinetic energy (E_{k_f}) and final potential energy (E_{g_f}) compare to E_{g_i}? (5.3) K/U
   (a) $E_{g_i} < E_{k_f} + E_{g_f}$
   (b) $E_{g_i} = E_{k_f} - E_{g_f}$
   (c) $E_{g_i} = E_{k_i} + E_{g_f}$
   (d) $E_{k_i} - E_{g_f}$
7. Which energy transformation takes place during photosynthesis? (5.4) K/U
   (a) nuclear energy to radiant energy
   (b) radiant energy to chemical energy
   (c) chemical energy to thermal energy
   (d) thermal energy to chemical energy
8. Which energy source is renewable? (5.4) K/U
   (a) coal
   (b) biofuel
   (c) natural gas
   (d) nuclear power

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

9. Work equals mass times acceleration. (5.1) K/U
10. When a force acts on an object in a direction different from the direction of displacement, work can be calculated if the angle between the force and displacement vectors is known. (5.1) K/U
11. The kinetic energy of an object can be increased or decreased by doing work on it. (5.2) K/U
12. A bicycle moving at 5 m/s at sea level has more potential energy than a motionless bicycle at the top of a mountain. (5.2) K/U
13. The law of conservation of energy does not apply to electrical motors that are less than 100 % efficient. (5.3) K/U
14. Washing half loads of laundry instead of full loads conserves energy. (5.4) K/U
15. A motor that does 500 J of work in 1 s has the same power as a motor that does 500 J of work in 2 s. (5.5) K/U

To do an online self-quiz,
GO TO NELSON SCIENCE

CHAPTER 5 REVIEW

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

Knowledge

Select the best answer from the four alternatives.

1. Which equation correctly describes the mechanical work done on an object? (5.1) K/U
   (a) $W_{\text{net}} = \dfrac{\Delta E}{\Delta T}$
   (b) $W_{\text{net}} = \dfrac{E_{\text{out}}}{E_{\text{in}}} \times 100\ \%$
   (c) $W_{\text{net}} = v_{\text{i}}^2 + 2a\Delta d$
   (d) $W_{\text{net}} = F_{\text{net}}(\cos\theta)\Delta d$
2. Which form of energy is wind energy? (5.3) K/U
   (a) chemical
   (b) electrical
   (c) kinetic
   (d) thermal
3. Into which two forms of energy is the electrical energy that powers a light bulb transformed? (5.3) K/U
   (a) radiant energy and thermal energy
   (b) thermal energy and chemical energy
   (c) chemical energy and elastic energy
   (d) elastic energy and kinetic energy
4. Which type of energy is commonly a by-product of any kind of energy transformation? (5.4) K/U
   (a) radiant energy
   (b) thermal energy
   (c) chemical energy
   (d) elastic energy
5. Which sequence of processes is correctly ordered from least efficient to most efficient in terms of energy transformations? (5.4) K/U
   (a) generation of electricity with a hydroelectric power plant, photosynthesis, riding a bicycle, generation of electricity with a nuclear power plant
   (b) generation of electricity with a nuclear power plant, riding a bicycle, photosynthesis, generation of electricity with a hydroelectric power plant
   (c) photosynthesis, generation of electricity with a nuclear power plant, generation of electricity with a hydroelectric power plant, riding a bicycle
   (d) riding a bicycle, generation of electricity with a hydroelectric power plant, generation of electricity with a nuclear power plant, photosynthesis

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

6. Mechanical work is calculated by multiplying the magnitude of a force by the amount of time it is applied. (5.1) K/U
7. Energy can be defined as the ability to do work. (5.2) K/U
8. Gravitational energy is a form of kinetic energy. (5.3) K/U
9. Energy, work, and time are scalar quantities, but power is a vector quantity. (5.5) K/U

Match each term on the left with the most appropriate description on the right.

10. (a)	biofuel	(i)	may interfere with bird flight paths
(b)	geothermal energy	(ii)	harnesses the energy of moving water
(c)	tidal generation	(iii)	may produce air pollutants when burned
(d)	wind turbines	(iv)	available in unlimited supply deep underground (5.4) K/U

Write a short answer to each question.

11. Describe the relationship among displacement, work, and force. (5.1) K/U C
12. A 2000 kg rock rolls down a hillside at 40 m/s and crashes into a large tree, where it comes to rest. The tree does not move. How much work was done on the tree by the rock? Explain your answer. (5.1) T/I C
13. Explain how thermal energy is related to kinetic energy. (5.2) K/U
14. A skydiver with a mass of 60.0 kg reaches a terminal velocity of 40.0 m/s and continues to fall at that velocity until she opens her parachute. What is the kinetic energy of the skydiver as she falls at terminal velocity? (5.2) T/I
15. What do the terms m, g, and h in the equation $E_g = mgh$ stand for? (5.2) K/U
16. Describe the main energy transformations that occur when an apple falls from a tree. (5.3) C K/U

17. What are the two types of electrical energy? (5.3) K/U
18. What methods may architects use to take advantage of the Sun's radiant energy for heating a building? (5.4) K/U
19. In your own words, define efficiency as it applies to a device designed to perform an energy transformation. (5.4) K/U
20. Which nuclear process do conventional nuclear power plants take advantage of to produce electricity? (5.4) K/U
21. Why are fossil fuels called fossil fuels? (5.4) K/U
22. What unit is commonly used when measuring the energy rating of an electrical appliance? (5.5) K/U
23. Explain the difference between energy and power. (5.5) K/U

Understanding

24. (a) Describe a situation in which pushing a wheelbarrow filled with soil does no work.
    (b) Describe two different situations in which pushing a wheelbarrow full of soil does work. (5.1) K/U
25. A boy is mowing a lawn with a push mower. The handle of the mower makes a 30° angle with the ground. Explain how you would determine the horizontal component of the applied force if you know the total force exerted by the boy on the mower handle. (5.1) K/U
26. A 2100 kg car starts from rest and accelerates at a rate of 2.6 m/s^2 for 4.0 s. Assume that the force acting to accelerate the car is acting in the same direction as its motion. How much work has the car done? (5.1) T/I
27. A roller coaster drops from the initial high point and continues to rise and fall as it follows the track up and down. Explain how transformations between kinetic and potential energy are related to the rising and falling of the roller coaster. (5.2, 5.3) K/U
28. A force does positive work on a moving object. (5.2) K/U A
    (a) How is the velocity of the object affected?
    (b) How is the energy of the object affected?
29. A 1900 kg car slows down from a speed of 25.0 m/s to a speed of 15.0 m/s in 6.25 s. How much work was done on the car? (5.2) T/I
30. A 68 kg rock climber who is 320 m above the ground descends down a rope at 1.5 m/s. Using the ground as a reference point, determine the total mechanical energy of the rock climber at this point. (5.2) T/I
31. A 2600 kg truck travelling at 72 km/h slams on the brakes and skids to a stop. The frictional force from the road is 8200 N. Use the relationship between kinetic energy and mechanical work to determine the distance it takes for the truck to stop. (5.2) T/I
32. Describe two energy transformations taking place at a hydroelectric power plant. Specify the energy types before and after each transformation. (5.3) K/U
33. Describe the energy transformations occurring in each of the following situations. (5.3) K/U C
    (a) Grass is growing.
    (b) A vibrating guitar string is heard around the room.
    (c) A stuntman falls and lands safely on a trampoline.
    (d) The black asphalt on a driveway gets warm in the hot sun.
34. A bungee jumper has a mass of 73 kg and falls a distance of 120 m before the bungee catches and sends the jumper upward. Use the law of conservation of energy to calculate the speed of the jumper just before the bungee catches. (5.3) T/I
35. Compact fluorescent light bulbs are more efficient than incandescent bulbs. (5.4) K/U
    (a) Describe the energy transformations taking place in a light bulb.
    (b) Explain the difference in efficiency of the two types of bulbs in terms of energy transformations.
36. (a) Define the term *renewable energy resource* and give an example.
    (b) Define the term *non-renewable energy resource* and give an example. (5.4) K/U
37. A roller coaster descends 55 m from the top of the first high point to the first low point in the track. The roller coaster converts gravitational potential energy to kinetic energy with an efficiency of 50.0 %. What is the velocity of the roller coaster at the bottom of the first low point? (5.4) T/I
38. A compact fluorescent bulb is 17.0 % efficient. (5.4) T/I
    (a) How much energy input would be required for the bulb to produce 252 J of light energy?
    (b) What type of energy is the waste output and how much would be created?
39. A car's engine is only 12 % efficient at converting chemical energy in gasoline into mechanical energy. If it takes 18 000 N of force to keep the car moving at a constant speed of 21 m/s, how much chemical energy would be needed to move the car a distance of 450 m at this speed? (5.4) T/I

40. Copy and complete **Table 1** in your notebook. (5.4) K/U

Table 1 Energy Sources

Energy source	Renewable or non-renewable?
biofuel	
coal	
geothermal	
hydroelectric	
natural gas	
nuclear	
oil	
solar	
wind	
wood	

41. Explain how each of the following renewable energy sources is used to generate electricity or other forms of usable energy. Describe all the energy transformations involved, including the energy form before and after each transformation. For each energy source, explain why it is considered renewable in terms of the original source of the energy. (5.4) K/U
    (a) hydroelectric
    (b) tidal
    (c) geothermal
    (d) wind
42. How many watts of power does a man with a weight of 600.0 N have when he climbs a flight of stairs 3.0 m high in 5.0 s? (5.5) T/I
43. A girl pushes a merry-go-round with a force of 120 N for a distance of 6.0 m. If she does this in 2.0 s, how much power does she have? (5.5) T/I
44. A baseball player puts a baseball on a batting tee. The baseball bat is able to deliver 4.0×10^5 W of power and is in contact with the ball for 0.70 ms and a distance of 1.4 cm. The mass of the ball is 145 g. What is the net force applied to the ball and what is its average acceleration? (5.5) T/I

Analysis and Application

45. Give an example of a force that causes displacement but does no work. (5.1) K/U
46. In this chapter you learned that many activities that people think of as work are not classified as work by scientists. (5.1) K/U C A
    (a) Describe two physical activities that are considered to be work in a workplace situation but are not work in the scientific sense. These should be activities for which people are paid. Explain in terms of the directions of force and displacement why they are not work.
    (b) Describe two physical activities that are classified as work in *both* the everyday sense and the scientific sense. These should be activities for which people might be paid. Explain your classification in terms of the directions of force and displacement.
47. A man is loading boxes onto a shelf that is 2.2 m high. It took 98 N of force to lift a 10.0 kg box at a constant speed onto the shelf. (5.1) T/I
    (a) How much work was done by the man lifting the box?
    (b) How much work was done by gravity?
    (c) What was the net work done on the box?
    (d) Is it possible to determine the net work done on the box in this problem without knowing the mass of or the force exerted by the man? Explain.
48. A weightlifter lifts a 155 kg weight with 1910 N of force overhead to a height of 2.80 m. The weight then falls back down to the ground. Determine the net force acting on the weight for both the lift and the drop and create an *F*-*d* graph for this situation. (5.1) T/I C
49. A boy drops a 0.50 kg rock off of a 22 m high bridge into a river below. (5.2, 5.3) T/I
    (a) Using the river as a reference point, what is the initial potential energy of the rock?
    (b) What is the kinetic energy of the rock just before it hits the water?
    (c) What is the final speed of the rock just before it hits the water?
50. A 1800 kg trick airplane is 450 m in the air. At this point the plane takes a dive with an initial speed of 42 m/s and accelerates to 64 m/s, dropping a total distance of 120 m. (5.2, 5.3) T/I
    (a) Using the ground as a reference point, calculate the potential energy of the plane at the beginning and the end of the dive.
    (b) What is the kinetic energy of the plane at the beginning and at the end of the dive?
    (c) What is the total work done on the plane during its dive?

51. A car travels at a constant velocity of 60.0 km/h on a level highway for a distance of 10.0 km. The car accelerates briefly to 70.0 km/h to pass another car and then returns to 60.0 km/h as it ascends a hill. The car accelerates to 65 km/h as it descends the other side of the hill, even though the driver has taken her foot off the accelerator. (5.1, 5.2, 5.3) T/I A
    (a) Identify the times when the car's engine was doing work on the car. Explain your answers.
    (b) Describe the energy transformations taking place when the engine was doing work.
    (c) Describe the energy transformations when the engine was not doing work.
52. In this chapter you learned that solar cells are only relatively efficient at transforming radiant energy into electrical energy. Green plants are even less efficient at converting radiant energy to chemical energy. (5.4) C A
    (a) Explain why low efficiency in these processes is less of a concern than it is in the processes that convert chemical energy in fossil fuels to useful forms of energy.
    (b) Both biofuels and fossil fuels store chemical energy that originally came to Earth as sunlight. If the original source is the same, why are biofuels classified as a renewable energy resource and fossil fuels as a non-renewable energy resource?
53. A man is pushing an 11 kg lawn mower against a frictional force of 86 N for 22 m. (5.4) T/I
    (a) What is the minimal force that the man needs to push with in order to keep the lawnmower moving?
    (b) Calculate the minimum amount of energy required for the man to push the lawnmower the required distance.
    (c) If the man uses 2180 J of energy to push the mower at a constant speed what is his efficiency?
54. Traditional farmhouses often have covered, open porches along the sides of the house (**Figure 1**). (5.4) K/U A

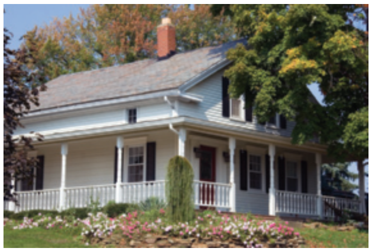


Figure 1

    (a) Explain why this is a useful passive solar design.
    (b) Explain why planting deciduous trees around a house is a better passive solar design than planting coniferous trees.
55. Two students perform an experiment to study the efficiency of an energy conversion and test the law of conservation of energy. For an energy conversion device, they choose a playground slide. They take measurements as different students slide down the slide. They use a speed gun to measure the final speed of the sliders at the bottom of the slide. They measure the height difference between the top and bottom of the slide to be 3.0 m. (5.4, 5.5) K/U T/I C A
    (a) Derive the equation for the efficiency of transformation of potential energy into kinetic energy. Explain why the mass of the sliders is not needed.
    (b) If the speed of a slider at the bottom of the slide is 5.0 m/s, what is the efficiency of the energy transformation?
    (c) Describe one factor that contributes to loss of efficiency.
    (d) Identify a type of energy that potential energy was converted to (do not use "kinetic energy" in your answer).
    (e) Write a word equation using types of energy that expresses the law of conservation of energy for this energy transformation.
    (f) Was the law of conservation of energy violated? Explain.
56. Describe three ways to conserve electrical energy by making small changes to your daily habits. (5.4) K/U C
57. An incandescent bulb is only 5.0 % efficient. How much waste thermal energy is produced by a 100.0 W bulb in 1.0 h? (5.4, 5.5) T/I
58. The transformation efficiency of a nuclear power plant is more than twice that of a gasoline-powered vehicle. (5.4) K/U C
    (a) Describe the energy transformations that take place in a nuclear power plant when it is generating electricity.
    (b) Describe two disadvantages of using nuclear power as a source of electrical energy.
59. A microwave oven operates at 1275 W. Assume electricity costs 5¢/kWh. (5.5) T/I A
    (a) What is the cost of heating a cup of soup in a microwave for 2 min?
    (b) Describe two possible "hidden" costs of heating the cup of soup in the microwave.

60. The hand-cranked radio is a fairly recent innovation. These radios draw power from a battery that is charged by turning a hand crank (**Figure 2**). People buy them so that they will have a source of information during natural disasters that result in loss of electrical power. Describe all the energy transformations that take place in a hand-cranked radio, beginning with the *original* source of energy and continuing step-by-step to the type of energy emitted by the radio. (5.3) K/U C A

Figure 2

61. The Sun is the original source of most of the energy we use on Earth. This is true not only of renewable energy sources, but also non-renewable sources. (5.4) C A
    (a) Identify two renewable sources of energy for which the Sun is the original source of energy. Explain how the energy is transferred from the Sun to the sources you chose.
    (b) Identify a renewable source of energy for which the Sun is not the original source of energy.
    (c) Identify two non-renewable sources of energy for which the Sun is the original source of energy. Explain how the energy is transferred from the Sun to the sources you chose.
    (d) Explain how two forms of energy can both have the Sun as their source, and yet one is classified as renewable and the other non-renewable.

62. Define and describe each of the following sources of renewable energy. For each source, describe the type of region in Canada where it would most easily be produced. (5.4) K/U C
    (a) biofuels
    (b) geothermal
    (c) tidal
    (d) wind

63. A 610 kg racehorse is able to accelerate from rest to a speed of 14 m/s in only 1.1 s. (5.5) T/I
    (a) Assume that the acceleration of the racehorse is constant. What is the distance required by the horse to reach this speed?
    (b) What is the minimum amount of energy required by the horse to reach this speed?
    (c) How much power does the horse have during acceleration?

64. A cyclist is competing in a race and decides to pass some fellow cyclists who are getting tired. The initial speed of the cyclist is 21 km/h and he has 3.0×10^2 W of power. If the bicycle is able to convert 92 % of the input energy into kinetic energy, how fast will the cyclist be travelling after 4.0 s? The combined mass of the cyclist and the bicycle is 78 kg. (5.3, 5.4) T/I

Evaluation

65. Use what you have learned about energy sources to discuss which changes Ontario could make in order to reduce its use of some energy sources while increasing its use of other energy sources. Answer the questions below. (5.4) K/U A
    (a) Explain which non-renewable sources should be phased out and replaced with other sources.
    (b) For those sources you would phase out, justify your choice in terms of availability, cost, or environmental concerns.
    (c) For the alternative sources you propose, explain why they should be favoured in terms of availability, cost, or environmental concerns.
    (d) Explain your reasoning for not including the alternative sources that you did not propose.

66. The use of solar, or photovoltaic, cells is a well-known method of transforming sunlight into useful electrical energy. Evaluate the generation of electricity using photovoltaic cells. (5.4) K/U A
    (a) Describe two advantages and two disadvantages of using photovoltaic cells.
    (b) Describe any hidden costs you can think of that may arise from the production, transportation, or transmission of the energy.
    (c) Compare the suitability of using photovoltaic cells for generating electrical energy in Canada to that of other regions of North America.

Reflect on Your Learning

67. What did you learn in this chapter that you found most surprising? Explain. C

68. (a) What questions do you still have about work, power, and energy?
    (b) What methods can you use to find answers to your questions? K/U C A

69. Has the information you have learned in this chapter changed your opinion about any environmental issues related to energy? Explain. C A

70. In this chapter you learned that potential energy is the ability of an object to do work because of forces in the environment. We commonly consider objects to have gravitational potential energy because of the work gained or lost due to their change in height. There were other types of energy mentioned that can also be considered a form of potential energy. In your own words describe how the following types of energy can be considered potential energy and give an example of each. C A
    (a) thermal energy
    (b) nuclear energy
    (c) chemical energy

Research

GO TO NELSON SCIENCE

71. Canada has extensive deposits of oil sands (**Figure 3**). Oil sands can be processed to yield petroleum, and it has been suggested as an alternative to North America's dwindling reserves of crude oil. Research the potential of oil sands as an energy resource. Write a few paragraphs discussing its advantages and disadvantages in terms of cost, practicality, and environmental impact. T/I C

Figure 3

72. Canada is second only to China in the production of hydroelectric power. Canada is one of the few countries that generate the majority of their electrical energy from hydroelectricity. Research hydroelectricity in Canada, and write a short report that addresses the advantages and disadvantages of using this resource. Discuss the benefits and hazards of expanding Canadian hydroelectric power. T/I C

73. No energy conversion device is 100 % efficient. Some energy always escapes as waste heat. This heat does not disappear, but it is lost because it cannot be converted to useful work. Many strategies designed to conserve energy in the home are based on preventing heat from escaping. Research the causes of heat loss in appliances and home heating systems. Pay special attention to newer technologies and improvements in building materials that prevent heat loss from homes. Create a news report summarizing your findings. Be sure to explain heat loss in terms of the law of conservation of energy. T/I C A

74. Animals such as glow-worms and fireflies have long been known to convert chemical energy into light (**Figure 4**). Write a page on bioluminescence describing how it works and what animals use it for. How efficient are these methods at converting chemical energy into light? Are there any applications that humans have adapted from bioluminescence? C

Figure 4 Some organisms like these insect larvae called glow-worms can transform the chemical energy in food into radiant energy.

75. For most sources, stored energy is easily converted into some form of usable energy. Chemical energy is easily combusted to create kinetic energy, the kinetic energy of rivers is used to turn turbines to create electrical energy, and electrical energy is easily converted into light and heat for our homes. However, the converse is not true. Any excess energy that is generated is not easily converted back into a form that can be stored for later use. Research different types of devices that are used to store excess energy and write a page describing how they work and any problems they might have with efficiency or functionality. C

CHAPTER 6

Thermal Energy and Society

KEY CONCEPTS

After completing this chapter you will be able to

- describe the differences among temperature, thermal energy, and heat
- solve problems involving the quantity of heat and apply the concept to situations involving heat exchange
- explain the temperature changes involved in changes of state, and mathematically determine the energy involved
- describe the impact of heating and cooling systems on society and the environment

How Can People Utilize Thermal Energy?

The sight of steaming hot water shooting like a fountain out of Earth is impressive; it serves as an indicator of the potential that lies below the surface of Earth. Geothermal energy from deep within Earth's crust can be used for heating and cooling, and generating electricity. At a depth of 6000 km, Earth's temperature can be close to 5000 °C. Underground reservoirs of water are heated, sometimes forming large pockets of steam. As you will learn in this chapter, thermal energy that is even a short distance below Earth's surface can be effectively utilized for heating and cooling systems.

At the edges of Earth's tectonic plates, hot magma is much closer to the surface than it is in other areas of Earth's lithosphere. This results in concentrations of volcanoes, hot springs, and geysers such as those in the "Ring of Fire" in the Pacific Ocean. In the past, people in these areas tapped into Earth's geothermal energy to cook their food, to bathe, to treat illness, and to heat their homes.

Humans are now developing new ways to heat water and other fluids by pumping them into Earth's hot interior and then bringing them to the surface. The development of such techniques is important in the reduction of greenhouse gases because, unlike the burning of fossil fuels, geothermal energy technologies do not directly release pollutants into the air or contribute to climate change.

In this chapter, you will explore the differences among thermal energy, temperature, and heat. You will learn how to calculate quantities of thermal energy absorbed or released by an object as it changes temperature or changes state. You will also learn how thermal energy transfer is involved in heating and cooling systems, including geothermal systems, and you will explore the environmental and societal impacts of these systems.

STARTING **POINTS**

Answer the following questions using your current knowledge. You will have a chance to revisit these questions later, applying concepts and skills from the chapter.

1. Define the terms "hot" and "cold" by relating them to the concept of energy that you learned in Chapter 5.
2. What does temperature tell you about a substance?
3. What happens to the particles of a solid when it changes into a liquid? How is energy involved in the process?

Mini Investigation

Will It Pop?

Skills: Predicting, Observing, Analyzing

SKILLS HANDBOOK A2.1

Different substances react to thermal energy in different ways. In this experiment, you will think about the differences between air and water and the ability of each to absorb thermal energy. ✋

✋ Tie back long hair during the investigation.

Equipment and Materials: tea light, 2 balloons, water

1. Predict what will happen when a flame touches an air-filled balloon and when a flame touches a water-filled balloon.
2. Your teacher will fill one balloon with water and tie it off. Your teacher will then blow up the second balloon with air until it is the same size as the water balloon.
3. Your teacher will have a station set up with a lit tea light. Your teacher will briefly touch the surface of the air-filled balloon to the flame from the tea light. Record your observations.
4. While holding the water balloon over a large container, your teacher will briefly touch the water-filled balloon to the flame of the tea light. Record your observations.

A. What role does thermal energy play in the case of
- the water-filled balloon?
- the air-filled balloon? T/I

6.1 Warmth and Coldness

When you dip your toe into a swimming pool to test the warmth of the water before jumping in, you are using your sense of touch to determine how hot or cold a substance is. While touch helps us sense large differences in warmth or coldness, small differences can go unnoticed. For example, you might be able to feel the difference in warmth between an egg in the refrigerator and an egg frying in a skillet, but you might not notice any difference between an egg in the refrigerator and the same egg left on a kitchen counter for a minute or two. What is the difference between a cold egg and a hot egg? Why is a cold egg cold and a hot egg hot? How can we accurately measure the warmth and coldness of objects?

Warmth and Coldness Are Produced by the Vibrations of Atoms and Molecules

During the eighteenth century, scientists thought that warmth and coldness were produced by a massless fluid called "caloric." Scientists believed that the amount of this fluid in the universe was constant and that it flowed naturally from warmer objects to colder objects. In 1798, English scientist Benjamin Thompson (known as Count Rumford) published his investigations showing that caloric did not exist. Count Rumford noticed that when holes were drilled into large, solid iron cylinders used to build cannons, the drilling apparatus and the iron cylinders would become very hot even though both had been lukewarm at the beginning of the process. This seemed to imply that caloric was not flowing from a warmer object to a colder one, but was being created by rubbing two objects together. You might experience the same effect by rubbing the palms of your hands together very rapidly (**Figure 1**).

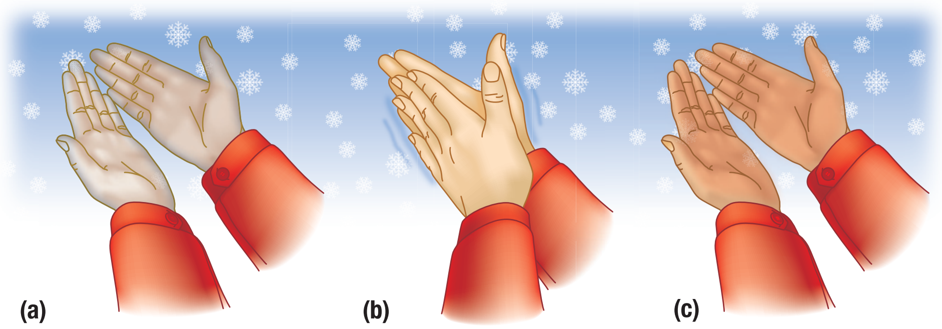


Figure 1 (a) Your bare hands become cold outside in the winter. (b) When you rub your hands together, they warm up. (c) What causes your hands to become warm?

Up until this time, scientists thought that materials could become hot only if they are in contact with even hotter materials that could transfer caloric to them. Count Rumford's investigations caused scientists to lose confidence in the caloric theory's explanation of why objects are hot or cold. Instead, scientists began to explain warmth and coldness using a theory called the kinetic molecular theory.

kinetic molecular theory the theory that describes the motion of molecules or atoms in a substance in terms of kinetic energy

The **kinetic molecular theory** is based on the idea that matter is composed of particles (atoms and molecules) that attract each other and have kinetic energy. It is the kinetic energy that causes particles to be in a state of constant motion. In a solid, such as ice, the particles are held in fixed positions by the forces of attraction between them and vibrate because of the kinetic energy they possess (**Figure 2(a)**). If a solid is warmed up, the particles remain in fixed positions but begin to vibrate more rapidly. According to the kinetic molecular theory, an increase in the motion of the particles of a substance makes the substance feel warmer; a decrease in the motion makes the substance feel colder.

In a liquid, such as liquid water, the particles have more kinetic energy than those of a solid. This causes the particles to vibrate even more rapidly and also to move from place to place, although not very far from each other. This additional motion gives liquids the ability to flow (**Figure 2(b)**).

The particles of a gas have more kinetic energy than those of liquids or solids. This causes them to vibrate and move from place to place much farther and more rapidly than the particles of liquids or solids (**Figure 2(c)**).

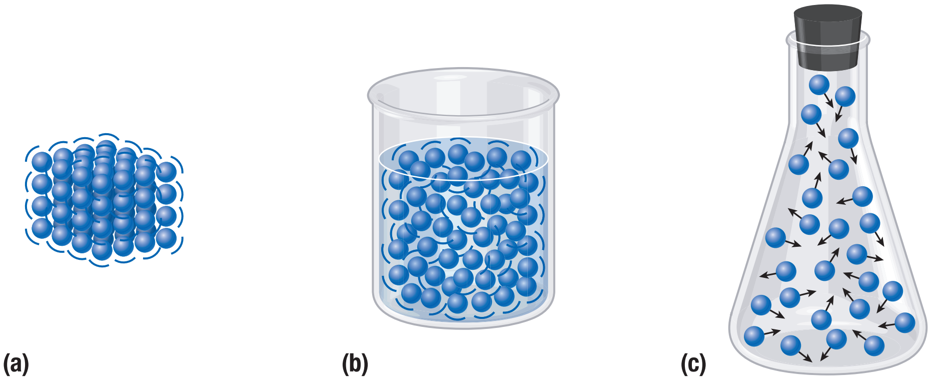


Figure 2 (a) Particles in solids are very close together and can only move back and forth within a very limited range. (b) Particles in liquids are very close together but are able to move and slide past one another. (c) Particles in gases can move freely past each other.

Thermal Energy

Particles of matter possess many forms of kinetic energy and potential energy. Much of the kinetic energy is associated with the motion of the atoms or molecules, while much of the potential energy is associated with the force of attraction between these particles. The total amount of kinetic and potential energy possessed by the particles of a substance is called **thermal energy**.

thermal energy the total quantity of kinetic and potential energy possessed by the atoms or molecules of a substance

In general, the amount of thermal energy within an object determines how fast its particles move (vibrate) and, therefore, how hot or cold the object is. When an object or substance absorbs thermal energy, it warms up; when it releases thermal energy, it cools down. Thermal energy can be transferred from a warmer object to a colder object, but not from a colder object to a warmer object. The thermal energy of an object can also be transformed into other forms of energy. Thermal energy, like all other types of energy, is measured using the SI unit of joules.

Temperature and Thermometers

If thermal energy is responsible for the warmth or coldness of an object, how can we measure the amount of thermal energy that an object has? Unfortunately, there is no way to measure the total amount of thermal energy in an object, because it is impossible to measure the kinetic energy and potential energy of *every* particle within the object. However, there is a way to measure the average kinetic energy of the particles, which gives us an indication of how hot or cold an object is. **Temperature** is a measure of the average kinetic energy of the particles in a substance.

temperature a measure of the average kinetic energy of the particles in a substance

Notice that temperature is a measure of *average* kinetic energy, not total kinetic energy. The reason is that the particles of an object at a particular temperature have different amounts of kinetic energy; some particles move faster than others. However, the majority of the particles of a warmer object move faster than the majority of the particles of a colder object. So, the temperature of a warmer object is higher than the temperature of a colder object.

Temperature is often measured using a mercury or an alcohol thermometer. These thermometers have a narrow, sealed glass tube containing liquid mercury or coloured alcohol. When a thermometer is placed within a liquid or gas, the particles of the substance bump into the glass of the thermometer (**Figure 3(a)**). As the temperature of the substance increases, these collisions cause the particles of the glass to vibrate with greater intensity. In turn, the fast-moving particles of the glass tube collide with the slower-moving particles of the mercury or alcohol inside the tube, making these particles move faster as well. The faster-moving particles of mercury or alcohol begin to spread out and take up more space. This causes the liquid in the thermometer to move higher up the tube and give a higher temperature reading (**Figure 3(b)**).

If a thermometer is placed in a substance that is colder than the thermometer, the glass particles of the thermometer collide with the slower-moving particles of the substance, transferring energy to them. This causes the glass particles to slow down. In turn, the particles of the mercury or alcohol in the thermometer collide with the slower-moving particles of the glass, transferring energy to them. This causes the mercury or alcohol particles of the thermometer to slow down, take up less space, move lower in the tube, and give a lower temperature reading.

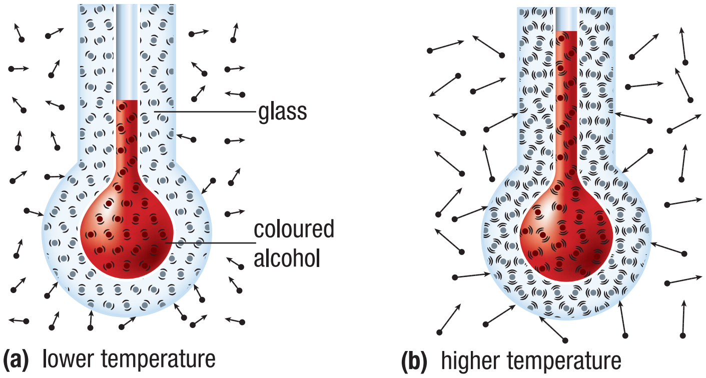


Figure 3 (a) The particles of a thermometer in a colder environment move with less vigour and occupy a smaller volume than in (b) a warmer environment.

Temperature Scales

The units for temperature depend on the type of scale that is used. For example, the Celsius scale is used by weather forecasters to report air and water temperatures and by nurses when they measure the temperature of our bodies when we are sick. The **Celsius scale** is named after Anders Celsius, a Swedish scientist, who based the scale on the temperature at which water boils and freezes. On the Celsius scale, pure water freezes at 0 °C and boils at 100 °C.

Celsius scale the temperature scale based on the boiling point and freezing point of water

Another temperature scale is the Fahrenheit scale. The **Fahrenheit scale** was invented by Daniel Gabriel Fahrenheit and is based on the temperature at which a brine (salt-water) solution freezes and boils. On the Fahrenheit scale, pure water freezes at 32 °F and boils at 212 °F. Although the Fahrenheit scale is still used in the United States, it is not an SI unit.

Fahrenheit scale the temperature scale based on the boiling point and freezing point of brine

Scientists often use the **Kelvin scale**, instead of the Celsius or Fahrenheit scale, to measure temperature. The Kelvin scale was created by Irish scientist William Thomson, also known as Lord Kelvin. The Kelvin scale is not based on the freezing and boiling points of water or brine, but on the total amount of thermal energy that substances possess. The lowest point on the Kelvin scale, called absolute zero, is the temperature at which the particles of a substance have slowed down so much that they hardly move at all. At this point, the kinetic energy of the particles approaches zero. Absolute zero, or 0 K, occurs at approximately −273 °C. The SI unit for temperature is the kelvin (K). To convert from the Kelvin scale to the Celsius scale (and vice versa), you can use the following equations, where T_C is the temperature in degrees Celsius and T_K is the temperature in kelvins:

Kelvin scale the temperature scale developed using absolute zero as the point at which there is virtually no motion in the particles of a substance

$$T_C = T_K - 273$$

$$T_K = T_C + 273$$

In the following Tutorial, you will use these equations to convert a given temperature from one scale to the other.

Tutorial 1 Converting between Celsius and Kelvin Temperature Scales

In the following Sample Problems, you will convert degrees Celsius to kelvins, and kelvins to degrees Celsius.

Sample Problem 1

Ethyl alcohol boils at a temperature of 78.3 °C. What is this temperature in kelvins?

Given: $T_C = 78.3\ °C$

Required: T_K

Analysis: $T_K = T_C + 273$

Solution: $T_K = T_C + 273$

$= 78.3 + 273$

$T_K = 351\ K$

Statement: Ethyl alcohol boils at 351 K.

Sample Problem 2

Ethyl alcohol freezes at 159 K. What is this temperature in degrees Celsius?

Given: $T_K = 159\ K$

Required: T_C

Analysis: $T_C = T_K - 273$

Solution: $T_C = T_K - 273$

$= 159 - 273$

$T_C = -114\ °C$

Statement: Ethyl alcohol freezes at −114 °C.

Practice

1. Convert each temperature to kelvins. T/I
   (a) 32 °C [ans: 305 K]
   (b) −10 °C [ans: 263 K]
   (c) 95 °C [ans: 368 K]
2. Convert each temperature to degrees Celsius. T/I
   (a) 200 K [ans: −73 °C]
   (b) 373 K [ans: 100 °C]
   (c) 298 K [ans: 25 °C]

Mini **Investigation**

Film Canister Thermometer

Skills: Observing, Analyzing, Evaluating

SKILLS HANDBOOK A2.1

In this activity, you will construct a film canister thermometer and compare its accuracy with that of a regular thermometer.

Equipment and Materials: thermometer; film canister with hole in its lid; beaker; plastic drinking straw; fine-tipped marker; ice water; food colouring; white glue

1. Push the straw through the hole in the lid of the film canister. The straw should be positioned so that it is just above the bottom of the canister, but not touching the bottom. Apply glue around the straw where it meets the canister lid to create a seal.
2. Use the regular thermometer to measure the temperature of the ice water.
3. Fill the canister half-full with ice water and add a drop or two of food colouring. Put the lid on the canister.
4. Use the marker to mark the level of the water on the straw. Label this with the temperature you measured in Step 2.
5. Allow the canister thermometer to warm up to room temperature overnight. Observe the canister thermometer the next day. As the canister thermometer warms up, the level of the coloured water in the straw will rise.
6. Find the room temperature using the regular thermometer. Mark this temperature on the straw.
7. Measure the distance between the two marks. Determine the number of degrees Celsius between the marks.
8. Create a scale that allows you to place 1 °C increments on the straw of the canister thermometer.
9. Put some cold tap water in a beaker. Use the canister thermometer to measure the temperature of the cold water. Check the reading by comparing it to the temperature you get using the regular thermometer.

A. Explain how the canister thermometer works. K/U T/I

B. Discuss the accuracy of this type of thermometer. K/U

C. Suggest some ways in which the design of the thermometer may be improved. T/I

D. How practical is the canister thermometer when measuring the temperature of a liquid? A

Thermal Energy, Temperature, and Physical State

Substances increase in temperature (warm up) when they absorb thermal energy and decrease in temperature (cool down) when they release thermal energy. When thermal energy is absorbed by a solid substance, the solid eventually melts into a liquid. The temperature at which a solid melts into a liquid is called the **melting point**. Conversely, when a liquid is cooled down, it eventually freezes. The **freezing point** is the temperature at which the liquid begins to freeze into a solid. For most substances, the melting point is the same as the freezing point.

If a liquid absorbs enough thermal energy, it eventually becomes a gas. The temperature at which a liquid changes into a gas is called the **boiling point**. Conversely, when a gas releases thermal energy, it cools down and eventually condenses into a liquid. The temperature at which a gas changes into a liquid is called the **condensation point**. For most substances, the boiling point is the same as the condensation point.

melting point the temperature at which a solid changes into a liquid; equal to the freezing point for a given substance

freezing point the temperature at which a liquid changes into a solid; equal to the melting point for a given substance

boiling point the temperature at which a liquid changes into a gas; equal to the condensation point for a given substance

condensation point the temperature at which a gas changes into a liquid; equal to the boiling point for a given substance

6.1 Summary

- Thermal energy is the total potential and the total kinetic energy possessed by the particles of a substance.
- Temperature is a measure of the average kinetic energy of the particles in a substance.
- The kinetic molecular theory states that as particles of matter gain kinetic energy, they move faster and the temperature of the substance increases. Similarly, as particles of matter lose kinetic energy, they move more slowly and the temperature of the substance decreases.
- Temperature can be measured using the Celsius scale, Fahrenheit scale, or Kelvin scale. Scientists typically use the Kelvin scale because kelvins are SI units.
- The equations $T_C = T_K - 273$ and $T_K = T_C + 273$ can be used to convert temperatures from one scale to the other.

6.1 Questions

1. Differentiate between temperature and thermal energy. K/U
2. Describe how the kinetic molecular theory explains the changes of state in substances. K/U
3. How does a mercury or an alcohol thermometer work? K/U
4. Copy **Table 1** in your notebook and fill in the missing values. K/U T/I

Table 1 Boiling Points of Various Substances

Substance	Boiling point (°C)	Boiling point (K)
sodium	882.9	
helium		4.22
copper	2567	
mercury		630

5. Research to find out more about how the caloric theory was disproved. T/I
6. Why does the volume of alcohol in a thermometer decrease when the thermometer is moved from a warm environment into a colder environment? K/U
7. What is the relationship between the freezing point and the melting point of most substances? K/U

GO TO NELSON SCIENCE

Heat

Thermal energy is responsible for an object's warmth or coldness; thermal energy affects an object's temperature. When an object absorbs thermal energy, its temperature rises; when the object releases thermal energy, its temperature falls. This occurs because a large component of the thermal energy of an object is the kinetic energy of its particles. However, the thermal energy of an object also includes the potential energy associated with the object's particles. How do the kinetic energy and the potential energy components of thermal energy affect the warmth and coldness (temperature) of objects?

Thermal Energy and Temperature

Since the amount of thermal energy in an object determines the object's temperature, it follows that two identical objects at the same temperature contain the same amount of thermal energy. However, this is only true if the two objects are made of the same material and have the same mass. For example, two iron nails, both with a mass of 1.0 g and both with a temperature of 22 °C, have the same amount of thermal energy (**Figure 1(a)**). However, if two objects are made of the same substance but their masses are different, then the amount of thermal energy that they have is different. For example, if an iron nail with a mass of 1.0 g and an iron nail with a mass of 2.0 g are both at a temperature of 22 °C, they do not have the same amount of thermal energy (**Figure 1(b)**). The more massive nail has more thermal energy than the less massive nail even though both nails have the same temperature.

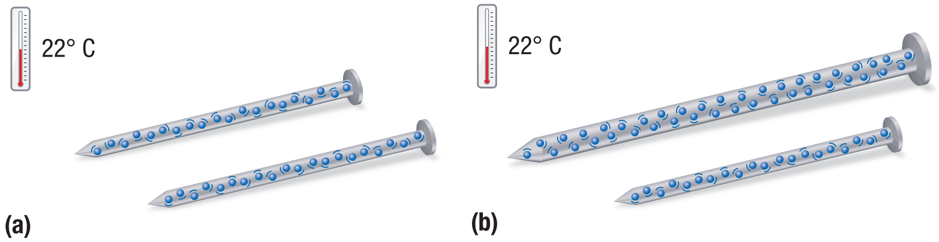


Figure 1 (a) Two 1.0 g iron nails at the same temperature (22 °C) have the same amount of thermal energy. (b) A 1.0 g iron nail and a 2.0 g iron nail at the same temperature do not have the same amount of thermal energy. The 2.0 g iron nail has twice as many vibrating iron atoms as the 1.0 g iron nail. So it has twice the thermal energy of the 1.0 g nail, even though both nails have the same temperature (22 °C).

This difference in thermal energy occurs because the more massive nail has more vibrating atoms of iron (twice as many). Since both nails are at the same temperature, their atoms are vibrating with the same average kinetic energy. However, the 2.0 g nail has twice as many vibrating atoms as the 1.0 g nail. So, the 2.0 g nail has twice as much *total* kinetic energy (and thermal energy) as the 1.0 g nail.

If two objects have the same mass and the same temperature, but they are made of two different substances, then they will likely contain different amounts of thermal energy. For example, an iron nail with a mass of 1.0 g and a temperature of 22 °C does *not* have the same amount of thermal energy as an aluminum nail with the same mass and temperature. This occurs because thermal energy includes both the kinetic *and* potential energy of a substance's particles. As a substance absorbs energy from its surroundings, part of this energy increases the kinetic energy of the substance's particles. The increase in kinetic energy, in turn, increases the temperature of the substance. Part of the absorbed energy also increases the potential energy of the particles. Note that an increase in potential energy does not increase the temperature of the substance. The proportion of the absorbed energy that goes toward increasing the potential energy of the particles is different in different substances.

Distinguishing between Thermal Energy and Heat

heat the transfer of thermal energy from a substance with a higher temperature to a substance with a lower temperature

Thermal energy is the sum of the potential and kinetic energies possessed by the particles of an object. However, **heat** is a term used in science to describe the transfer of thermal energy from a warmer object to a colder one. The word "heat" has many meanings in the English language, and it is commonly used to describe a substance that makes objects become warmer. For example, in the phrase, "a glass of hot water has more heat in it than a glass of cold water," the word "heat" is being used in a non-scientific way. In science, thermal energy, not heat, is responsible for an object's warmth or coldness. It would be more correct to say, "a glass of hot water has more *thermal energy* in it than a glass of cold water."

In most cases in science, it is preferable to use the word "heat" as a verb, not a noun. For example, in an investigation, you might be asked to use a hot plate *to heat* 250 mL of water to a temperature of 80 °C. This is the same as asking you to use a hot plate *to transfer thermal energy* to 250 mL of water until the water's temperature reaches 80 °C. Always use the word "heat" to mean the transfer of thermal energy, not the thermal energy itself.

WEB **LINK**

To learn more about the methods of heat transfer,

GO TO NELSON SCIENCE

Methods of Transferring Thermal Energy

Since heat is the transfer of thermal energy from a substance with a higher temperature to a substance with a lower temperature, there must be a method by which thermal energy can move from one object to another. In fact, there are several ways in which thermal energy can be transferred from one object to another. We will discuss three methods: thermal conduction, convection, and radiation.

TRANSFER OF THERMAL ENERGY BY CONDUCTION

thermal conduction the transfer of thermal energy that occurs when warmer objects are in physical contact with colder objects

Thermal energy can move from a warmer object to a colder object by a process called **thermal conduction** if the two substances physically touch each other. Thermal conduction occurs when the fast-moving particles of a warmer material collide with the slower-moving particles of a colder material. These collisions cause the slower-moving particles of the colder object to speed up and the faster-moving particles of the warmer object to slow down. As a result, the warmer object cools down (its temperature falls) as the colder object warms up (its temperature rises) (**Figure 2**).

You might notice this type of thermal energy transfer if you place a cold metal spoon in a cup of hot chocolate (**Figure 3**). In this case, the fast-moving particles of the hot chocolate collide with the slower-moving particles of the cold spoon, transferring thermal energy in the process. In turn, the fast-moving particles of the spoon's ladle (the part in the hot chocolate) collide with the slower-moving particles in the spoon's handle, causing the particles in the handle to move faster. This results in the thermal energy being transferred from the spoon's ladle to the spoon's handle until the thermal energy is evenly distributed throughout the spoon.

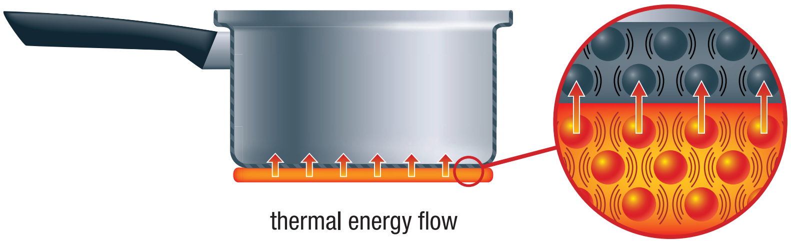


Figure 2 The transfer of thermal energy from an electric stove element to a metal pot involves thermal conduction.

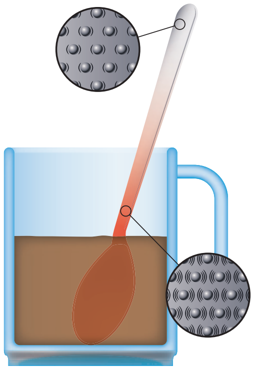


Figure 3 Thermal energy slowly moves up the spoon by conduction as the spoon sits in a hot liquid.

TRANSFER OF THERMAL ENERGY BY CONVECTION

In fluids (liquids and gases), thermal energy can be transferred by convection. **Convection** occurs when colder, denser fluid falls and pushes up warmer, less dense fluid. We can illustrate the process of convection by analyzing the changes that occur in a pot of water that is being heated on a stovetop (**Figure 4**). When the water particles nearest to the heat source absorb thermal energy, they move faster and spread farther apart. This means that the water near the bottom of the pot becomes less dense than the colder water above it. As a result, the colder, denser water above the warmer water sinks and pushes the warmer, less dense water upward. As the warmer water moves upward and farther away from the heat source, it cools down, increases in density, and falls into the warmer, less dense water below. This process repeats itself, resulting in a continuous **convection current** in which colder water moves downward (toward the heat source) and warmer water moves upward (away from the heat source). In this way, thermal energy spreads throughout the liquid.

convection the transfer of thermal energy through a fluid that occurs when colder, denser fluid falls and pushes up warmer, less dense fluid

convection current a current that occurs when a fluid is continuously heated; caused by warmer, less dense fluid being constantly pushed upward as colder, denser fluid falls downward

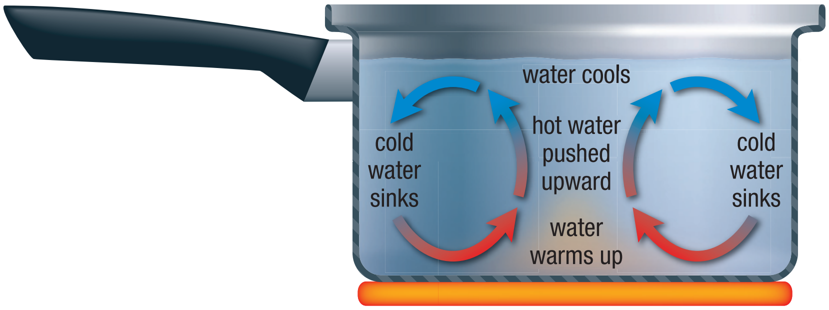


Figure 4 Convection currents cause the liquid in the pot to move around, spreading the thermal energy evenly.

Convection currents also form in gases, such as air, and are responsible for ocean breezes and other winds in the atmosphere. When the Sun's rays strike land, the air immediately above the land warms up and becomes less dense. As a result, colder, heavier air that is higher in the atmosphere falls downward, pushing the warmer air upward (**Figure 5**). This process repeats itself as the Sun continues to warm up the land, setting up continuous convection currents. People on the shore feel part of these currents as winds or breezes that move toward the shore.

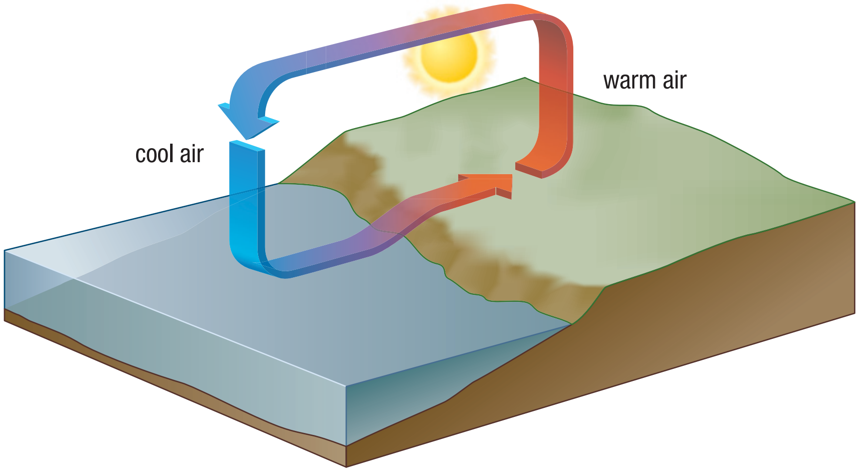


Figure 5 During the day, ocean breezes are created when cool air above the water falls downward and onto the land, pushing the warmer air over the land upward.

TRANSFER OF THERMAL ENERGY BY RADIATION

radiation the movement of thermal energy as electromagnetic waves

Thermal energy can also be transferred by radiation. **Radiation** is a thermal energy transfer that involves electromagnetic waves being emitted from sources such as lamps, flames, and the Sun. While the Sun is the largest source of radiant energy, all particles that have kinetic energy emit some radiant energy (**Figure 6**). These waves travel through materials such as air or glass or even through empty space.

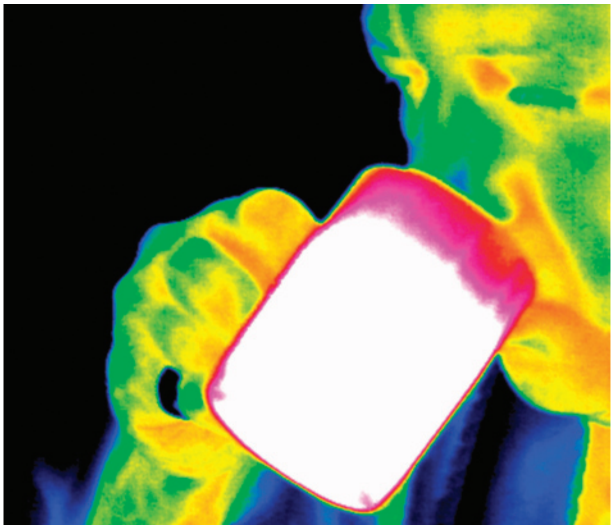


Figure 6 A thermal imaging camera can detect infrared radiation and produce an image called a thermogram.

Mini **Investigation**

Observing Convection

Skills: Performing, Observing, Analyzing

SKILLS HANDBOOK A2.1

This investigation will allow you to observe convection between warm and cold water.

Equipment and Materials: 4 identical bottles; blue and yellow food colouring; index card

1. Fill two of the bottles with hot tap water. Add 2 drops of yellow food colouring to each bottle.
2. Fill the other two bottles with cold tap water. Add 2 drops of blue food colouring to each bottle.
3. Use an index card to cover the top of one blue, cold water bottle. Make sure there is a good seal between the card and the bottle, and then flip the bottle over. Place this bottle on top of one of the yellow, hot water bottles. Hold onto the top bottle and slide the index card out, making sure the mouths of both bottles stay overlapped (**Figure 7**). Water will move back and forth between the bottles but it should not spill out. Observe what happens.
5. Repeat the activity, only this time put the other yellow, hot water bottle on top of the other blue, cold water bottle. Observe what happens.

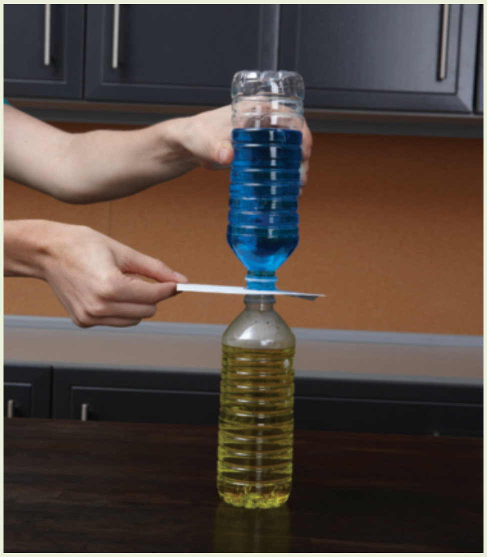


Figure 7

A. Use the concept of convection to explain what you observed in Step 3. K/U T/I

B. Explain why your observations were different in Step 4. T/I

THERMAL CONDUCTORS AND THERMAL INSULATORS

Have you ever touched a metal object and been surprised at how much colder it feels than a non-metal object in the same conditions? For example, a metal sink feels colder than a plastic kitchen countertop even though both are at room temperature. Why does this occur? Most metals are good conductors of thermal energy while many non-metals are poor conductors of thermal energy. Metals are called **thermal conductors** because they allow thermal energy to pass through them relatively easily and quickly. So, when your hand touches a metal sink, thermal energy moves easily and quickly from your hand to the metal sink. This makes the metal sink feel cold. The plastic countertop does not allow thermal energy to pass through it easily. So the thermal energy stays in your hand longer, and the countertop does not feel as cold as the sink. Since metals conduct thermal energy so well, we commonly make pots and pans out of metals so that thermal energy can be transferred easily and quickly from a hot stove or oven into raw food during cooking and baking.

thermal conductor a material that is a good conductor of thermal energy

Some materials, called **thermal insulators**, do not conduct thermal energy very well. These materials include many types of plastic. You might have noticed that the handles of many pots and pans and other kitchen utensils are made of plastic. The plastic handles prevent thermal energy from moving quickly from the metal pot into your hand. Still air (also called dead air) is also a very good thermal insulator. The atoms and molecules in gases such as air are farther apart than the particles in solids and liquids. So, gases tend to be poor conductors of thermal energy (good insulators). Animals make good use of this form of thermal insulation. Hair, fur, and feathers trap air between strands of matter (**Figure 8(a)**). The trapped air makes it difficult for thermal energy to move from the external environment into the animal's body or from the animal's body into the external environment (by thermal conduction or convection). Since hair, fur, and feathers help prevent the transfer of thermal energy, they are good thermal insulators.

thermal insulator a material that is a poor conductor of thermal energy

A good way to add thermal insulation to the walls of a house is by placing fibreglass batting (**Figure 8(b)**) or sheets of plastic foam (**Figure 8(c)**) in the wall spaces. Both of these materials contain trapped air that makes it difficult for thermal energy to pass from the outside into the house or from inside the house to the outside. Understanding which materials reduce the transfer of thermal energy can help people develop better building materials. Programs such as R-2000 and LEED (Leadership in Energy and Environmental Design) are intended to promote the use of effective thermal insulation in energy-efficient homes in Canada.

CAREER LINK

Many products are designed to take advantage of the thermal insulating properties of materials. To learn more about a career researching and designing thermal insulating products,

GO TO NELSON SCIENCE

WEB LINK

To learn more about the R-2000 and LEED programs,

GO TO NELSON SCIENCE

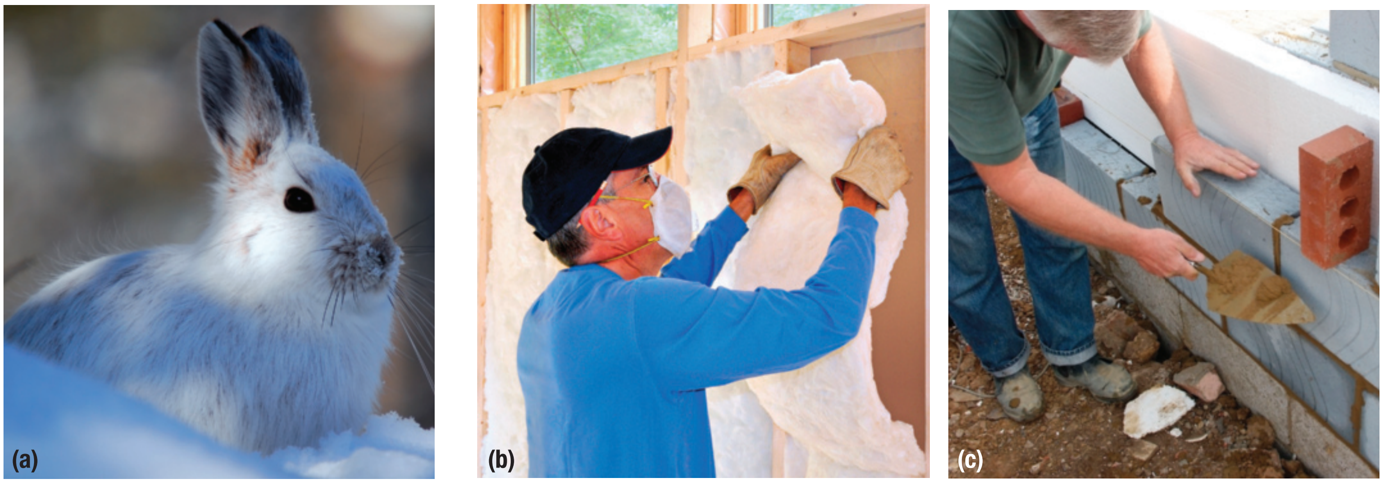


Figure 8 Thermal insulators include (a) fur, (b) fibreglass, and (c) foam insulation. All of these materials trap air and help to prevent the transfer of thermal energy from an object to the surroundings.

The best thermal insulator of all is a vacuum. A vacuum contains no particles or very few particles. So, thermal energy cannot be transferred by conduction or convection. A Thermos bottle (**Figure 9**) is an example of a device used to keep hot foods hot and cold foods cold by having a vacuum between an inner flask and an outer flask (usually made of glass). The inner glass flask is usually coated with a shiny, mirror-like layer to reflect any thermal energy that may be transferred by radiation.

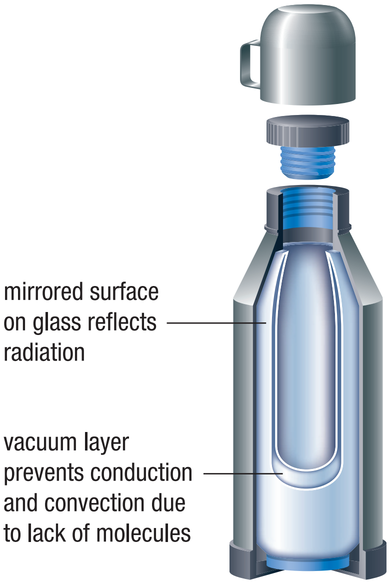

mirrored surface on glass reflects radiation
vacuum layer prevents conduction and convection due to lack of molecules

Figure 9 The layers of a Thermos bottle minimize conduction, convection, and radiation of thermal energy, keeping the contents cool or hot.

Thermal Energy Transformations

Furnaces, car engines, and incandescent lamps are all devices that transform one form of energy into another. For example, the internal combustion engine of a car is designed to transform the chemical energy in gasoline (input energy) into kinetic energy and thermal energy (output energies). The kinetic energy moves the car, and the thermal energy is transferred to the surroundings. Although some of the thermal energy may be used to heat the interior of the car in cold weather, most of the thermal energy is undesirable and a wasteful form of energy for the car since it does not contribute to the car's motion. As a result, scientists and engineers try to design energy-efficient devices—devices that transform as much input energy as possible into desired output energy.

THERMAL ENERGY TRANSFORMATION EFFICIENCY

The internal combustion engine is a device in which we would like to maximize the kinetic energy output and minimize the thermal energy output. However, in other devices, we may want to maximize the thermal energy output. For example, a furnace is used to heat a home or other building. In most furnaces, electrical energy or the chemical energy in fossil fuels (natural gas, propane, or oil) is the input energy and thermal energy is the desired output energy. A high-efficiency furnace is one that transforms a large proportion of the input energy into thermal energy. Electric furnaces are essentially 100 % efficient, meaning that virtually all of the input electrical energy is transformed into thermal energy. The most efficient natural gas furnaces are approximately 96 % efficient while older, less efficient versions are about 60 % efficient.

UNIT TASK **BOOKMARK**

You can apply what you have learned about thermal energy transformation efficiency to the Unit Task on page 360.

6.2 Summary

- Thermal energy is the total amount of kinetic energy and potential energy of the particles in a substance.
- Heat is the transfer of thermal energy from a warmer object to a cooler one.
- Thermal energy can be transferred in three different ways: by thermal conduction, by convection, or by radiation.

6.2 Questions

1. How do thermal energy, temperature, and heat differ? K/U
2. Define thermal conduction, convection, and radiation. K/U
3. Why does a tile floor feel much colder to your bare feet than a thick carpet does? K/U
4. If the efficiency of an electric furnace is 96 %, then 96 % of the input electrical energy is transformed into thermal energy. What is the other 4 % of the electricity transformed into? A
5. Are the following materials used because they are a good thermal conductor or a good thermal insulator? Explain why. K/U
   (a) copper pot
   (b) wooden spoon
   (c) metal ice-cube tray
   (d) down-filled sleeping bag

Heat Capacity

6.3

Have you ever warmed up a pot of water on a stove to make soup? If so, you may have noticed that it takes a relatively long time for the water to warm up. However, if you tried to warm up the same amount of oil in the same heating conditions you would notice that the oil warms up faster. Conversely, if a pot of water and a similar pot of oil at the same temperature are left on a stove to cool down, the oil will cool down faster than the water. Why do different substances warm up and cool down at different rates?

Specific Heat Capacity

It takes more energy to increase the temperature of 1.0 kg of water by 1 °C than it takes to increase the temperature of 1.0 kg of vegetable oil by 1 °C. The amount of energy needed to raise the temperature of 1 kg of a substance by 1 °C is called the **specific heat capacity (*c*)** of the substance.

The specific heat capacity of water is 4.18×10^3 J/(kg·°C), which is high in comparison with many other common liquids. The specific heat capacity of water indicates that it takes 4.18×10^3 J of energy to raise the temperature of 1 kg of water by 1 °C. Vegetable oil has a specific heat capacity of 2.0×10^3 J/(kg·°C), indicating that it takes approximately half as much energy to heat up 1 kg of vegetable oil by 1 °C than it takes to heat up 1 kg of water by 1 °C. So, a pot containing 1 kg of water at 10 °C uses a little more than twice as much energy to reach 100 °C as a pot containing 1 kg of vegetable oil at 10 °C. This difference occurs because water and vegetable oil are composed of different types of molecules. Different molecules require different amounts of energy to increase their kinetic energies by the same amount. Specific heat capacity also represents how much thermal energy is released when a substance cools down by 1 °C. **Table 1** gives the specific heat capacities of some common substances.

specific heat capacity (*c*) the amount of energy, in joules, required to increase the temperature of 1 kg of a substance by 1 °C; units are J/(kg•°C)

Table 1 Specific Heat Capacities of Common Substances

Substance	Specific heat capacity (J/(kg·°C))
water	4.18×10^3
ethyl alcohol	2.46×10^3
ice	2.1×10^3
aluminum	9.2×10^2
glass	8.4×10^2
iron	4.5×10^2
copper	3.8×10^2
silver	2.4×10^2
lead	1.3×10^2

Quantity of Heat

The total amount of thermal energy transferred from a warmer substance to a colder substance is called the **quantity of heat (*Q*)**. A quantity of heat calculation takes into account the mass (m) of the substance, the specific heat capacity (c) of the substance, and the change in the temperature (ΔT) that the substance undergoes as it heats up or cools down. The quantity of heat is measured in joules and can be calculated using the equation

$$Q = mc\Delta T$$

quantity of heat (*Q*) the amount of thermal energy transferred from one object to another

where Q is the quantity of heat in joules, m is the mass of the object in kilograms, c is the specific heat capacity of the substance in joules per kilogram degree Celsius, and ΔT is the change in temperature in degrees Celsius. The change in temperature (ΔT), is calculated by subtracting the initial temperature (T_1) of the substance from its final temperature (T_2) using the equation

$$\Delta T = T_2 - T_1$$

Note that if an object absorbs energy, its final temperature is greater than its initial temperature, and the value of ΔT is positive. However, if an object releases thermal energy, its final temperature is lower than its initial temperature, and the value of ΔT is negative. The following Tutorial demonstrates how to use the quantity of heat equation to calculate the amount of thermal energy absorbed by an object. The Tutorial also shows how to calculate the mass of an object or the specific heat capacity of an unknown object.

Tutorial 1 Quantity of Heat Calculations

The quantity of heat equation $Q = mc\Delta T$ can be used to calculate the quantity of thermal energy gained or lost by an object.

Sample Problem 1

When 200.0 mL of water is heated from 15.0 °C to 40.0 °C, how much thermal energy is absorbed by the water?

Since the quantity of heat equation is based on the mass of an object, we must first determine the mass, in kilograms, of 200.0 mL of water. To do this, we use the density of water, which is 1.0 g/mL. We then calculate the change in the temperature of the water using the equation $\Delta T = T_2 - T_1$. Finally, we use the quantity of heat equation, $Q = mc\Delta T$, along with the mass of the water, m, the specific heat capacity of water, c_W, and the change in temperature of the water, ΔT, to determine how much thermal energy is absorbed by the water.

Given: $V = 200.0\ \text{mL}$; $T_1 = 15.0\ °\text{C}$; $T_2 = 40.0\ °\text{C}$; $c_W = 4.18 \times 10^3\ \text{J/(kg} \cdot °\text{C)}$

Required: Q

Analysis: $\Delta T = T_2 - T_1$; $Q = mc\Delta T$

Solution:

$$m = 200.0\ \cancel{\text{mL}} \times \frac{1\ \cancel{\text{g}}}{1\ \cancel{\text{mL}}} \times \frac{1\ \text{kg}}{1000\ \cancel{\text{g}}}$$

$$m = 0.2000\ \text{kg}$$

$$\Delta T = T_2 - T_1$$

$$= 40.0\ °\text{C} - 15.0\ °\text{C}$$

$$\Delta T = 25.0\ °\text{C}$$

Now that we have calculated the mass of the water in kilograms and the change in temperature, we may use these values to calculate the quantity of heat:

$$Q = mc\Delta T$$

$$= (0.2000\ \cancel{\text{kg}})\left(4.18 \times 10^3\ \frac{\text{J}}{\cancel{\text{kg}} \cdot \cancel{°\text{C}}}\right)(25.0\ \cancel{°\text{C}})$$

$$Q = 2.09 \times 10^4\ \text{J}$$

Statement: The water absorbs 2.09×10^4 J of thermal energy.

LEARNING **TIP**

Mass Must Be in Kilograms When Using the Quantity of Heat Equation

Since the units for specific heat capacity are joules per kilogram degree Celsius, mass must be expressed in kilograms when using the quantity of heat equation.

Sample Problem 2

An empty copper pot is sitting on a burner. The pot has a mass of 1.2 kg and is at a temperature of 130.0 °C. If the pot cools to a room temperature of 21.0 °C, how much thermal energy does it release to the surroundings?

From Table 1 on page 281, we can determine that the specific heat capacity of copper is $3.8 \times 10^2\ \text{J/(kg} \cdot °\text{C)}$. As in Sample Problem 1, we need to find the change in temperature before calculating the quantity of thermal energy released by the pot using the quantity of heat equation.

Given: $m = 1.2\ \text{kg}$; $T_1 = 130.0\ °\text{C}$; $T_2 = 21.0\ °\text{C}$; $c = 3.8 \times 10^2\ \text{J/(kg} \cdot °\text{C)}$

Required: Q

Analysis: $\Delta T = T_2 - T_1$; $Q = mc\Delta T$

Solution: $\Delta T = T_2 - T_1$

$$= 21.0\ °\text{C} - 130.0\ °\text{C}$$

$$\Delta T = -109\ °\text{C}$$

$$Q = mc\Delta T$$

$$= (1.2\ \cancel{\text{kg}})\left(3.8 \times 10^2\ \frac{\text{J}}{\cancel{\text{kg}} \cdot \cancel{°\text{C}}}\right)(-109\ \cancel{°\text{C}})$$

$$Q = -5.0 \times 10^4\ \text{J}$$

Statement: The copper pot releases 5.0×10^4 J of thermal energy as it cools to 21.0 °C.

Sample Problem 3

A block of iron starts off at a temperature of 22.0 °C. It is heated to 100.0 °C by placing it in boiling water. The quantity of thermal energy required for this temperature change to occur is 4.91×10^5 J. Calculate the mass of the iron block.

From Table 1 on page 281, we can determine that the specific heat capacity of iron is 4.5×10^2 J/(kg•°C). As in Sample Problems 1 and 2, we need to find the change in temperature before we can calculate the mass of the iron block using the quantity of heat equation.

Given: $T_1 = 22.0$ °C; $T_2 = 100.0$ °C; $c = 4.5 \times 10^2$ J/(kg•°C), $Q = 4.91 \times 10^5$ J

Required: m, mass of iron

Analysis: $\Delta T = T_2 - T_1$; $Q = mc\Delta T$

Solution:

$$\begin{aligned} \Delta T &= T_2 - T_1 \\ &= 100.0\ °\text{C} - 22.0\ °\text{C} \\ \Delta T &= 78.0\ °\text{C} \end{aligned}$$

Rearrange the quantity of heat equation to solve for mass.

$$Q = mc\Delta T$$

$$m = \frac{Q}{c\Delta T}$$

$$m = \frac{4.91 \times 10^5\ \cancel{\text{J}}}{\left(4.5 \times 10^2\ \frac{\cancel{\text{J}}}{\text{kg}\bullet \cancel{°\text{C}}}\right)(78.0\ \cancel{°\text{C}})}$$

$$m = 14\ \text{kg}$$

Statement: The iron block has a mass of 14 kg.

Practice

1. How much thermal energy is required to raise the temperature of 2.0 kg of water by 10.0 °C? T/I [ans: 8.4×10^4 J]
2. A glass window with a mass of 20.0 kg is heated to a temperature of 32.0 °C by the Sun. How much thermal energy is released by the window to the surroundings as it cools to 5.0 °C at night? T/I [ans: 4.5×10^5 J]
3. An aluminum block absorbs 1.0×10^4 J of energy from the Sun when its temperature increases by 5.0 °C. What is the mass of the block? T/I [ans: 2.2 kg]

The Principle of Thermal Energy Exchange

The **principle of thermal energy exchange** states that when a warmer object comes in contact with a colder object, thermal energy is transferred from the warmer object to the colder object until all of the thermal energy is evenly distributed in both objects. In other words, the object with the higher temperature transfers thermal energy to the object with the lower temperature until both objects have the same temperature. If you use the quantity of heat equation to calculate the thermal energy released by the warmer object (Q_{released}) and the thermal energy absorbed by the colder object (Q_{absorbed}), the two values are equal in magnitude but opposite in sign. Q_{released} is negative since ΔT is negative, and Q_{absorbed} is positive since ΔT is positive. Considering the law of conservation of energy, this makes sense. Thermal energy, like all other forms of energy, cannot be destroyed; it can only be transferred or transformed. In this case, the thermal energy is transferred from a warmer object to a colder object.

principle of thermal energy exchange when thermal energy is transferred from a warmer object to a colder object, the amount of thermal energy released by the warmer object is equal to the amount of thermal energy absorbed by the colder object

This conclusion assumes that the thermal energy remains in the two objects being studied and is not released to the surroundings. In most circumstances, however, some thermal energy will be released to the surrounding air, container, or surfaces.

Mathematically, Q_{released} and Q_{absorbed} should add to zero, since they represent equal amounts, but have opposite signs:

$$Q_{\text{released}} + Q_{\text{absorbed}} = 0$$

The following Tutorial demonstrates how the quantity of heat equation and the principle of thermal energy exchange may be used to calculate the specific heat capacities, masses, or temperatures of various objects.

Tutorial 2 Using the Principle of Thermal Energy Exchange to Determine Mass, Temperature, and Specific Heat Capacity

By mathematically combining the quantity of heat equation, $Q = mc\Delta T$, with the principle of thermal energy exchange, $Q_{\text{released}} + Q_{\text{absorbed}} = 0$, we can calculate the specific heat capacity, mass, or temperature of an object.

Sample Problem 1

A 60.0 g sample of metal is heated to 100.0 °C before being placed in 200.0 mL of water with an initial temperature of 10.0 °C. The metal–water combination reaches a final temperature of 15.6 °C. Determine the identity of the metal.

In this situation, the metal releases thermal energy and the water absorbs thermal energy. Use the data given to calculate the specific heat capacity of the metal, and then use the specific heat capacity and **Table 1** on page 281 to identify the metal.

Given: We will use the subscripts "m" for metal and "w" for water and let V_w represent the volume of the water.

metal: $m_m = 60.0\text{ g} = 0.0600\text{ kg}$; $T_{1m} = 100.0\text{ °C}$; $T_{2m} = 15.6\text{ °C}$

water: $V_w = 200.0\text{ mL}$; $T_{1w} = 10.0\text{ °C}$; $T_{2w} = 15.6\text{ °C}$; $c_w = 4.18 \times 10^3\text{ J/(kg}\cdot\text{°C)}$

Required: c_m, specific heat capacity of the metal

Analysis: $Q_{\text{released}} + Q_{\text{absorbed}} = 0$; $Q = mc\Delta T$

Solution: Since the quantity of heat equation is based on the mass of a substance, we must first calculate the mass of water, m_w, in kilograms, using the volume of water, V_w, provided and the density of water.

$$\begin{aligned} m_w &= 200.0\ \cancel{\text{mL}} \times \frac{1\ \cancel{\text{g}}}{1\ \cancel{\text{mL}}} \times \frac{1\text{ kg}}{1000\ \cancel{\text{g}}} \\ &= 0.2000\text{ kg} \end{aligned}$$

The specific heat capacity of the metal, c_m, can be calculated by mathematically combining the quantity of heat equation, $Q = mc\Delta T$, and the principle of thermal energy exchange equation, $Q_{\text{released}} + Q_{\text{absorbed}} = 0$. We do this by substituting $Q = mc\Delta T$ for the metal and the water into $Q_{\text{released}} + Q_{\text{absorbed}} = 0$, remembering that the metal loses thermal energy and the water gains thermal energy.

$$m_m c_m \Delta T_m + m_w c_w \Delta T_w = 0$$

$$(0.0600\ \text{kg})(c_m)(15.6\ °\text{C} - 100\ °\text{C}) + (0.2000\ \text{kg})\left(4.18 \times 10^3\ \frac{\text{J}}{\text{kg}\cdot °\text{C}}\right)(15.6\ °\text{C} - 10.0\ °\text{C}) = 0$$

$$(0.0600\ \text{kg})(c_m)(-84.4\ °\text{C}) + (0.2000\ \cancel{\text{kg}})\left(4.18 \times 10^3\ \frac{\text{J}}{\cancel{\text{kg}}\cdot \cancel{°\text{C}}}\right)(5.6\ \cancel{°\text{C}}) = 0$$

$$(-5.064\ \text{kg}\cdot °\text{C})(c_m) + 4681.6\ \text{J} = 0\ \text{(two extra digits carried)}$$

$$(-5.064\ \text{kg}\cdot °\text{C})(c_m) = -4681.6\ \text{J}$$

$$c_m = \frac{-4681.6\ \text{J}}{-5.064\ \text{kg}\cdot °\text{C}}$$

$$c_m = 9.24 \times 10^2\ \text{J/(kg}\cdot °\text{C)}$$

Statement: The specific heat capacity of the metal is 9.24×10^2 J/(kg • °C), so the metal is aluminum.

Sample Problem 2

A sample of iron is heated to 80.0 °C and placed in 100.0 mL of water at 20.0 °C. The final temperature of the mixture is 22.0 °C. What is the mass of the iron?

In this problem, you first find the heat capacities of the substances in Table 1. Then decide which substance absorbed and which released thermal energy. Then use the combined quantity of heat/principle of thermal energy exchange equation to calculate the mass of the iron.

Given: iron: $T_{1i} = 80.0\ °\text{C}$; $T_{2i} = 22\ °\text{C}$; $c_i = 4.5 \times 10^2\ \text{J/(kg}\cdot °\text{C)}$

water: $m_w = 100.0\ \text{mL} = 100.0\ \text{g} = 0.1000\ \text{kg}$; $T_{1w} = 20.0\ °\text{C}$; $T_{2w} = 22\ °\text{C}$; $c_w = 4.18 \times 10^3\ \text{J/(kg}\cdot °\text{C)}$

Required: m_i, mass of the iron

Analysis: $Q_{\text{released}} + Q_{\text{absorbed}} = 0$; $Q = mc\Delta T$

Solution: $Q_{\text{released}} + Q_{\text{absorbed}} = 0$

$$m_i c_i \Delta T_i + m_w c_w \Delta T_w = 0$$

$$(m_i)\left(4.5 \times 10^2\ \frac{\text{J}}{\text{kg}\cdot °\text{C}}\right)(22.0\ °\text{C} - 80.0\ °\text{C}) + (0.1000\ \text{kg})\left(4.18 \times 10^3\ \frac{\text{J}}{\text{kg}\cdot °\text{C}}\right)(22.0\ °\text{C} - 20.0\ °\text{C}) = 0$$

$$(m_i)\left(4.5 \times 10^2\ \frac{\text{J}}{\text{kg}\cdot \cancel{°\text{C}}}\right)(-58.0\ \cancel{°\text{C}}) + (0.1000\ \cancel{\text{kg}})\left(4.18 \times 10^3\ \frac{\text{J}}{\cancel{\text{kg}}\cdot \cancel{°\text{C}}}\right)(2\ \cancel{°\text{C}}) = 0$$

$$(m_i)\left(-2.61 \times 10^4\ \frac{\text{J}}{\text{kg}}\right) + 8.36 \times 10^2\ \text{J} = 0$$

$$(m_i)\left(-2.61 \times 10^4\ \frac{\text{J}}{\text{kg}}\right) = -8.36 \times 10^2\ \text{J}$$

$$m_i = \frac{-8.36 \times 10^2\ \cancel{\text{J}}}{\left(-2.61 \times 10^4\ \frac{\cancel{\text{J}}}{\text{kg}}\right)}$$

$$m_i = 3.2 \times 10^{-2}\ \text{kg}$$

Statement: The mass of the iron is 3.2×10^{-2} kg.

Sample Problem 3

During an investigation, 200.0 g of silver is heated to 90.0 °C. The hot silver is then placed into 300.0 g of ethyl alcohol that has an initial temperature of 5.0 °C. Determine the final temperature of the silver–alcohol mixture.

Given: silver: $m_s = 200.0 \text{ g} = 0.2000 \text{ kg}$; $T_{1s} = 90.0\ °\text{C}$; $c_s = 2.4 \times 10^2 \text{ J/(kg}\cdot°\text{C)}$

ethyl alcohol: $m_a = 300.0 \text{ g} = 0.3000 \text{ kg}$; $T_{1a} = 5.0\ °\text{C}$; $c_a = 2.46 \times 10^3 \text{ J/(kg}\cdot°\text{C)}$

Required: T_2, final temperature of the silver–ethyl alcohol mixture

Analysis: $Q_{\text{released}} + Q_{\text{absorbed}} = 0$; $Q = mc\Delta T$

Solution: $Q_{\text{lost}} + Q_{\text{gained}} = 0$

$$m_s c_s \Delta T_s + m_a c_a \Delta T_a = 0$$

$$(0.2000 \cancel{\text{kg}})\left(2.4 \times 10^2 \frac{\text{J}}{\cancel{\text{kg}}\cdot°\text{C}}\right)(T_2 - 90.0\ °\text{C}) + (0.3000 \cancel{\text{kg}})\left(2.46 \times 10^3 \frac{\text{J}}{\cancel{\text{kg}}\cdot°\text{C}}\right)(T_2 - 5.0\ °\text{C}) = 0$$

$$\left(48 \frac{\text{J}}{°\text{C}}\right)(T_2 - 90.0\ °\text{C}) + \left(738 \frac{\text{J}}{°\text{C}}\right)(T_2 - 5.0\ °\text{C}) = 0$$

$$\left(48 \frac{\text{J}}{°\text{C}}\right)T_2 - 4320 \text{ J} + \left(738 \frac{\text{J}}{°\text{C}}\right)T_2 - 3690 \text{ J} = 0$$

$$\left(786 \frac{\text{J}}{°\text{C}}\right)T_2 - 8010 \text{ J} = 0$$

$$\left(786 \frac{\text{J}}{°\text{C}}\right)T_2 = 8010 \text{ J}$$

$$T_2 = \frac{8010 \text{ J}}{786 \frac{\text{J}}{°\text{C}}}$$

$$T_2 = 1.0 \times 10^1\ °\text{C}$$

Statement: The final temperature of the ethyl silver–alcohol mixture is 1.0×10^1 °C.

Practice

1. Sun-Young places a 2.0 kg block of aluminum that had been heated to 100.0 °C in 1.5 kg of ethyl alcohol with an initial temperature of 18.0 °C. What is the final temperature of the mixture? T/I [ans: 45 °C]
2. A metal bar with a mass of 4.0 kg is placed in boiling water until its temperature stabilizes at 100.0 °C. The bar is then immersed in 500.0 mL of water with an initial temperature of 20.0 °C. The mixture reaches a temperature of 35.0 °C. What is the specific heat capacity of the metal bar? T/I [ans: $1.2 \times 10^2 \text{ J/(kg}\cdot°\text{C)}$]

Thermal Expansion and Contraction

thermal expansion the expansion of a substance as it warms up

As a substance absorbs thermal energy, some of this energy is transformed into kinetic energy. So the particles spread out and increase in volume. The increase in the volume of an object due to an increase in its temperature is called **thermal expansion**.

An understanding of thermal expansion is important to civil engineers, who design various types of structures. For example, metal-framed windows require rubber spacers to account for any changes in size caused by temperature changes. Bridges require special joints called expansion joints to prevent pressure from bending the metal components of the bridge on hot summer days (**Figure 1(a)**), and concrete sidewalks have spaces between the slabs to make room for expansion that occurs as temperatures rise (**Figure 1(b)**).

Likewise, when substances cool down, their particles release kinetic energy to the surroundings and the substance decreases in volume, resulting in **thermal contraction**. All substances that expand in warmer weather contract in colder weather. Civil engineers must keep these points in mind.

thermal contraction the contraction of a substance when it cools down

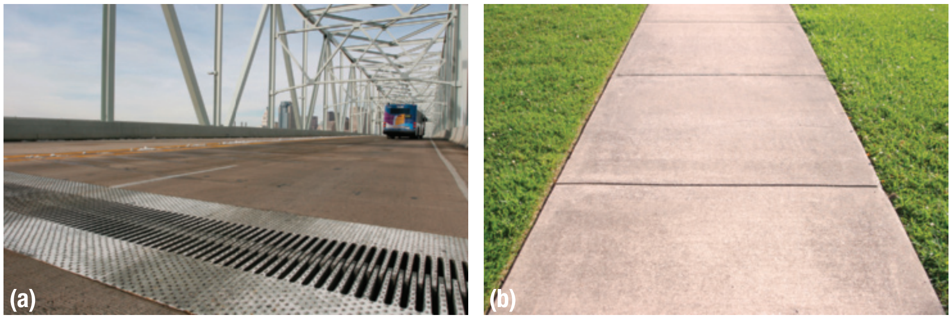


Figure 1 (a) Bridges have expansion joints to allow expansion during hot temperatures and contraction during cold temperatures. (b) Likewise, space must be left between concrete slabs to keep sidewalks from cracking when they expand in the heat and contract in the cold.

6.3 Summary

- Specific heat capacity is the amount of heat needed to raise the temperature of a 1 kg sample of a substance by 1 °C.
- The quantity of heat, or amount of thermal energy absorbed or released by an object, can be calculated using the equation $Q = mc\Delta T$.
- The principle of heat exchange states that thermal energy moves from a warm object to a cooler one until both objects reach a new constant temperature. This principle can be represented by the equation $Q_{\text{released}} + Q_{\text{absorbed}} = 0$.
- The absorption or release of thermal energy results in thermal expansion or contraction.

Investigation 6.3.1

Specific Heat Capacity of Brass (p. 304)

In this investigation, you will use the equations $Q = mc\Delta T$ and $Q_{\text{released}} + Q_{\text{absorbed}} = 0$ to calculate the specific heat capacity in a laboratory setting.

6.3 Questions

1. What is specific heat capacity? What does it tell you? K/U
2. Calculate the amount of thermal energy required to increase the temperature of 25.0 g of silver from 50.0 °C to 80.0 °C. K/U T/I
3. Calculate the amount of thermal energy released when 260.0 g of ice cools from −1.0 °C to −20.0 °C. K/U T/I
4. A 50.0 g sample of metal releases 1520 J of thermal energy when its temperature drops from 100.0 °C to 20.0 °C. What is the metal? K/U T/I
5. Calcium has a specific heat capacity of 6.3×10^2 J/(kg•°C). Determine the final temperature of a 60.0 g sample of calcium if it starts at 10.0 °C and absorbs 302 J of thermal energy. K/U T/I
6. A bar of pure gold is heated to 95.0 °C. The specific heat capacity of gold is 1.29×10^2 J/(kg•°C). The gold is placed into 500.0 mL of ethyl alcohol initially at a temperature of 25.0 °C. The final temperature of the mixture is 27.0 °C. What is the mass of the gold? K/U T/I
7. Danielle cools a 2.0 kg metal object to a temperature of −25.0 °C. She places the metal in 3.0 L of pure water initially at a temperature of 40.0 °C. The final temperature of the mixture is 36.0 °C. What is the specific heat capacity of the metal? K/U T/I
8. A 1.50×10^2 g piece of brass (specific heat capacity 3.80×10^2 J/(kg•°C)) is submerged in 400.0 mL of water at 27.7 °C. What is the original temperature of the brass if the mixture has a temperature of 28.0 °C? K/U T/I
9. Explain why temperature changes are important for civil engineers to consider when designing and evaluating building structures. K/U A
10. Research more about thermal expansion and contraction and how it is dealt with in the design of homes, schools, or other structures. Choose one innovation related to this topic and write a brief report. T/I C

GO TO NELSON SCIENCE

6.4 States of Matter and Changes of State

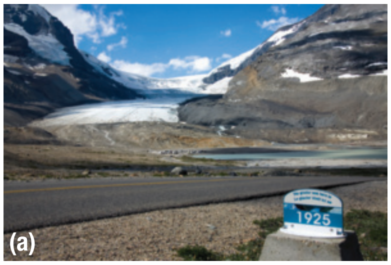


Figure 1 (a) The blue sign shows how far the Athabasca glacier has retreated since 1925. (b) Glacier ice melting into liquid water

Glaciers are huge masses of ice and snow that once covered most of Earth's surface. Many of the world's glaciers are retreating at an alarming rate. This means that they are getting smaller. The Athabasca glacier near Banff, Alberta, has retreated over 1.5 km in the last 120 years (**Figure 1(a)**). Scientists know that global warming is responsible for the retreat of the glaciers. Warm temperatures cause the ice and snow of a glacier to melt into liquid water (**Figure 1(b)**). The liquid water flows away from the glacier, forming rivers, lakes, and streams that make their way to the oceans. If the melted ice is not replaced by new ice, the glacier will retreat.

States of Matter

Water, and all other forms of matter, can exist in three different physical states, or phases: solid, liquid, and gas. The kinetic molecular theory described in Section 6.1 explains the differences between these physical states. In a solid, strong forces of attraction (bonds) hold the particles in fixed positions. The particles of a solid vibrate, but they cannot easily slide past each other or move from place to place. This gives solids their rigidity and allows them to maintain their shape. The particles of a liquid are also attracted to each other. However, in liquids, the particles have more kinetic energy than the particles of a solid. This causes the liquid's particles to vibrate more than the particles of a solid, and also to slide past each other and move from place to place. This gives liquids the ability to flow and pour. Like solids and liquids, the particles of a gas are attracted to each other. However, gas particles have much more kinetic energy than the particles of solids and liquids. The particles of a gas vibrate more vigorously than the particles of solids and liquids, and they move large distances past each other. This gives gases their ability to flow and to fill expandable containers like balloons and tires with great pressure.

Changes of State

When solids, liquids, or gases absorb or release enough thermal energy, they may change state (**Figure 2**). For example, a solid can change into a liquid and a liquid can change into a gas. When a substance absorbs thermal energy, the particles of the substance begin to move faster and farther apart. Note that the thermal energy is not really "absorbed"; it is transformed into kinetic energy and potential energy of the substance's particles. Remember that energy is always conserved. It can be transformed from one form into another, but it cannot be destroyed.

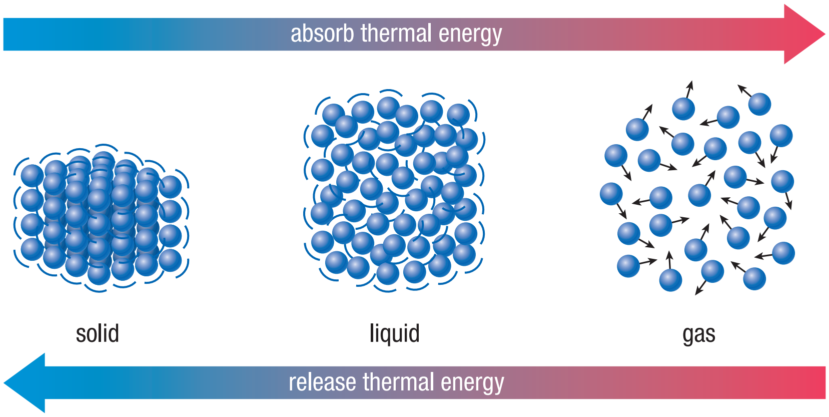


Figure 2 A change of state requires a change in the thermal energy of the substance.

Let us consider what happens to a sample of ice initially at −10 °C when it is continuously heated. When the ice is placed on the hot plate, its initial temperature is −10 °C (**Figure 3(a)**). As the ice absorbs thermal energy, its particles begin to vibrate more vigorously. This warms up the ice and increases its temperature. As the particles absorb more thermal energy, the forces of attraction are not strong enough to hold the particles in fixed positions. Eventually, the solid reaches its melting point, where the particles begin to slide past each other and move from place to place. At this point, the solid begins to change into a liquid (**Figure 3(b)**). The melting point of water is 0 °C. This change of state is called melting, or **fusion**. Eventually, all of the ice becomes liquid water (**Figure 3(c)**). Notice that thermal energy continues to be absorbed during the melting process, but the temperature does not change—it remains at 0 °C until the last ice crystal has melted into liquid water.

fusion the process by which a solid changes to a liquid

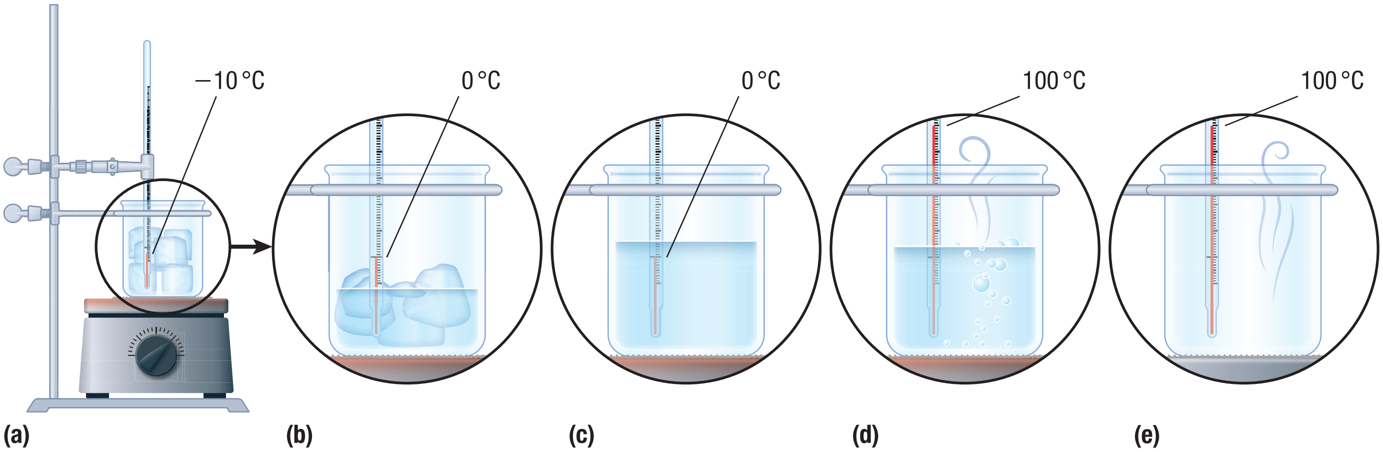


Figure 3 (a) Ice warms up. (b) As the ice reaches its melting point of 0 °C, it begins to change into a liquid because of the absorption of thermal energy. (c) As the ice–liquid water mixture is continuously heated, it continues to absorb thermal energy but stays at a temperature of 0 °C until the ice has completely melted. (d) The liquid water continues to absorb thermal energy until its temperature reaches its boiling point of 100 °C. At this point, enough thermal energy has been absorbed for it to begin to change into a gas, in this case water vapour. (e) The temperature remains at 100 °C until all of the liquid has changed to water vapour.

As the liquid water continues to absorb thermal energy, its particles move faster and farther apart. This warms up the liquid and increases its temperature. As the speed of the particles increases, the forces of attraction become weaker, and it becomes more difficult for the particles to stay together. Eventually, the liquid reaches its boiling point, at which the particles have enough kinetic energy to completely break away from each other. At the boiling point, the liquid water changes into a gas called water vapour (**Figure 3(d)**). The boiling point of water is 100 °C. This change of state is called evaporation or vaporization. Eventually, all of the liquid evaporates into a gas (**Figure 3(e)**). Notice that thermal energy continues to be absorbed during the boiling process, but the temperature does not change—it remains at 100 °C until the last drop of water has changed into water vapour. Changes of state occur whenever any material is heated from a solid to a liquid to a gas. The only difference is that every material has a different melting point and a different boiling point.

Removal of thermal energy reverses this process. In this case, a gas cools down into a liquid and a liquid cools down into a solid. The change of a gas into a liquid is called condensation, and the change of a liquid into a solid is called freezing. In some cases, it is possible for a substance to go directly from a solid to a gas, or vice versa, without ever becoming a liquid. This special change of state is called sublimation. An example of sublimation occurs when ice cubes are kept in a freezer for a long period of time. The ice cubes become smaller and smaller as they sublimate into water vapour.

Heating and Cooling Graphs

The changes in temperature that occur when a substance absorbs thermal energy can be shown in a graph called a **heating graph.** Similarly, the changes in temperature that occur when a substance releases thermal energy can be shown in a graph called a **cooling graph**. In both graphs, the vertical axis (*y*-axis) represents temperature and the horizontal axis (*x*-axis) represents the amount of thermal energy absorbed or released. **Figure 4(a)** is the heating graph for water, and **Figure 4(b)** is the cooling graph for water. An artist's illustration of the state of the water particles is shown above each graph.

heating graph a graph that shows the temperature changes that occur while thermal energy is absorbed by a substance

cooling graph a graph that shows the temperature changes that occur while thermal energy is being removed from a substance

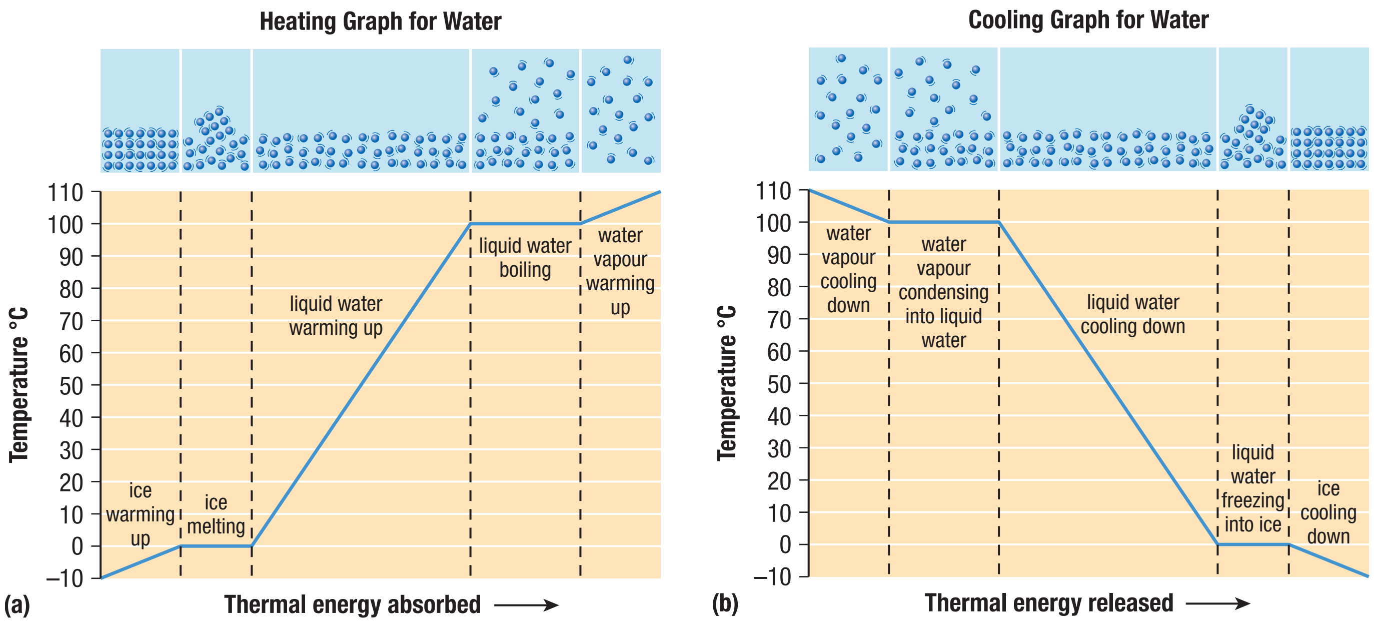


Figure 4 (a) A heating graph and (b) a cooling graph for water. The angled parts on each graph indicate a change in temperature and occur when only one state is present. The flat parts on each graph occur when more than one state is present. The flat parts indicate a constant temperature because one state is changing into another.

Notice the following key aspects of each graph:

- On the heating graph, thermal energy is being absorbed by the water molecules throughout the heating process. On the cooling graph, thermal energy is being released by the water molecules throughout the cooling process.
- Temperature changes occur only when one state is present. These changes are represented by the angled parts of each graph.
- The temperature remains constant during a change of state because thermal energy is being used to change the potential energy of the substance's particles, not their kinetic energy. On the heating graph, this occurs when a solid is changing into a liquid and when a liquid is changing into a gas. On the cooling graph, this occurs when a gas is changing into a liquid and when a liquid is changing into a solid. This is represented by the flat parts of both graphs.
- The heating graph shows a distinct melting point and boiling point. The cooling graph shows a distinct condensation point and freezing point. The melting and freezing points are both 0 °C, and the boiling and condensation points are both 100 °C. In general, melting and freezing occur at the same temperature, and boiling and condensation occur at the same temperature.

You may believe that the temperature of a substance should change while it is absorbing or releasing thermal energy because thermal energy affects the kinetic energy of particles. But why does the temperature not change during melting, freezing, boiling, or condensation?

Investigation **6.4.1**

Heating Graph of Water (p. 305)
In this activity, you will observe the temperature change as ice changes into water and create your own heating graph of water.

During melting and boiling, thermal energy must be absorbed by the particles of a substance. This absorbed energy is needed to break the bonds that hold the particles together. However, during condensation and freezing, thermal energy must be released by the particles of a substance. The released energy now allows the particles to move closer together and become more organized. In each of these situations, the change in thermal energy of the substance results in a change in potential energy of the particles. In other words, when a substance melts, boils, condenses, or freezes, the absorbed or released thermal energy is being transformed into potential energy, rather than kinetic energy. Since the kinetic energy of the particles does not change, the temperature of the substance remains constant during a change of state.

Latent Heat

As you have learned, when a substance absorbs or releases thermal energy during a change of state, its temperature remains constant. This absorbed or released thermal energy during a change of state is called the **latent heat (*Q*)** of the substance. The word "latent" means "hidden" because there is no measurable change in temperature. This thermal energy remains "hidden" until the opposite change of state occurs. For example, the thermal energy absorbed when ice melts into liquid water remains in the liquid water until it is released when the liquid water freezes back into ice. Latent heat is measured in joules. Every substance has a latent heat of fusion and a latent heat of vaporization. The **latent heat of fusion** is the amount of thermal energy absorbed when a substance melts or released when it freezes. Note that these energy values are the same for a particular substance because the amount of energy absorbed when a solid melts into a liquid is the same as the amount of energy released when that liquid freezes back into a solid. We use the term "latent heat of fusion" for both values.

The **latent heat of vaporization** is the amount of thermal energy absorbed when a substance evaporates or released when it condenses. As with latent heat of fusion, the energy values required to cause a substance to evaporate or condense are the same, and we use the term "latent heat of vaporization" for both values.

The **specific latent heat (*L*)** of a substance is the amount of thermal energy required for 1 kg of a substance to change from one state into another. Every substance has a different specific latent heat because every substance is composed of different particles (atoms or molecules). The **specific latent heat of fusion (L_f)** is the thermal energy required for 1 kg of a substance to melt or freeze (**Table 1**). The **specific latent heat of vaporization (L_v)** is the thermal energy required for 1 kg of a substance to boil or condense (Table 1). The SI unit for specific latent heats is joules per kilogram (J/kg).

latent heat (*Q*) the total thermal energy absorbed or released when a substance changes state; measured in joules

latent heat of fusion the amount of thermal energy required to change a solid into a liquid or a liquid into a solid

latent heat of vaporization the amount of thermal energy required to change a liquid into a gas or a gas into a liquid

specific latent heat (*L*) the amount of thermal energy required for 1 kg of a substance to change from one state into another; measured in joules per kilogram (J/kg)

specific latent heat of fusion (L_f) the amount of thermal energy required to melt or freeze 1 kg of a substance; measured in joules per kilogram (J/kg)

specific latent heat of vaporization (L_v) the amount of thermal energy required to evaporate or condense 1 kg of a substance; measured in joules per kilogram (J/kg)

Table 1 Specific Latent Heats for Various Substances

Substance	Specific latent heat of fusion (L_f) (J/kg)	Melting point (°C)	Specific latent heat of vaporization (L_v) (J/kg)	Boiling point (°C)
aluminum	6.6×10^5	2519	4.0×10^5	10 900
ethyl alcohol	1.1×10^5	−114	8.6×10^5	78.3
carbon dioxide	1.8×10^5	−78	5.7×10^5	−57
gold	1.1×10^6	1064	6.4×10^4	2 856
lead	2.5×10^4	327.5	8.7×10^5	1 750
water	3.4×10^5	0	2.3×10^6	100

LEARNING **TIP**

Remember Units

As with all questions in physics, make sure the units in your calculations of latent heat match. Mass must be expressed in kilograms, and latent heat is expressed in joules since the units for specific latent heat are joules per kilogram.

Investigation **6.4.2**

Specific Latent Heat of Fusion for Ice (p. 306)

In this investigation, you will use the equations $Q = mc\Delta T$ and $Q = mL_f$ to determine the latent heat of fusion for melting ice.

To calculate the latent heat (Q) involved during a change of state, you can use the equations

$$Q = mL_f \text{ (for substances that are melting or freezing)}$$

$$Q = mL_v \text{ (for substances that are boiling or condensing)}$$

where m is the mass of the substance, L_f is the specific latent heat of fusion, and L_v is the specific latent heat of vaporization.

In the following Tutorial, you will use the specific latent heat of fusion (L_f) and specific latent heat of vaporization (L_v) to calculate the latent heat (Q), or total amount of thermal energy absorbed or released when a substance changes state. In some of the Sample Problems, you will also determine the amount of thermal energy absorbed or released when a substance warms up or cools down but does not change state. In those cases, you will use the quantity of heat equation ($Q = mc\Delta T$) that you learned about in Section 6.3. Note that Q represents both latent heat and quantity of heat. The reason is that both are measures of the amount of thermal energy absorbed or released. The only difference is that latent heat (Q) relates to a substance changing state (temperature remains constant), whereas the quantity of heat (Q) relates to a substance in a particular state (solid or liquid or gas) warming up or cooling down (temperature changes).

Tutorial 1 Calculating Latent Heat of Fusion or Vaporization

Remember that the latent heat equations $Q = mL_v$ and $Q = mL_f$ are used to calculate the amount of thermal energy required for a change of state to occur, whereas the quantity of heat equation $Q = mc\Delta T$ is used to calculate the amount of thermal energy absorbed or released when a solid, liquid, or gas warms up or cools down.

Sample Problem 1

How much thermal energy is released by 652 g of molten lead when it changes into a solid?

Since lead is changing from a liquid to a solid, a change of state is occurring. So, we should use the latent heat equation $Q = mL_f$ to solve this problem.

Given: $m = 652\text{ g} = 0.652\text{ kg}$; $L_f = 2.5 \times 10^4\text{ J/kg}$ (from Table 1)

Required: Q, latent heat of fusion

Analysis: $Q = mL_f$

Solution:
$$\begin{aligned} Q &= mL_f \\ &= (0.652\ \cancel{\text{kg}})(2.5 \times 10^4\text{ J/}\cancel{\text{kg}}) \\ Q &= 1.6 \times 10^4\text{ J} \end{aligned}$$

Statement: The 652 g of lead releases 1.6×10^4 J of thermal energy as it solidifies.

Sample Problem 2

Ethyl alcohol is a liquid at room temperature. How much thermal energy is absorbed when 135 g of ethyl alcohol at 21.5 °C is heated until all of it boils and turns into vapour?

This is a two-step calculation because the ethyl alcohol will first warm up from 21.5 °C to its boiling point of 78.3 °C (see Table 1 on p. 291) and then change from a liquid into a gas while its temperature remains at 78.3 °C. So there is a warming-up part and a change of state. We will represent the amount of thermal energy absorbed during the warming-up part with Q_1, and the amount of thermal energy absorbed during the change of state with Q_2.

We will use the quantity of heat equation, $Q_1 = mc\Delta T$, to calculate the amount of thermal energy absorbed during the warming phase. For this calculation, we need to use the specific heat capacity, c, of ethyl alcohol from Table 1 in Section 6.3 on page 281.

Then we will use the latent heat equation, $Q_2 = mL_v$, to calculate the amount of thermal energy absorbed during the change of state. For this calculation, we need to use the specific latent heat of vaporization, L_v, of ethyl alcohol from Table 1 in this section.

The total amount of thermal energy absorbed in the entire process, Q_{total}, is the sum of Q_1 and Q_2.

Given: $m = 135\ \text{g} = 0.135\ \text{kg}$; $c = 2.46 \times 10^3\ \text{J/(kg}\cdot{}^\circ\text{C)}$; $T_1 = 21.5\ {}^\circ\text{C}$; $T_2 = 78.3\ {}^\circ\text{C}$; $L_v = 8.6 \times 10^5\ \text{J/kg}$

Required: Q_{total}, total amount of thermal energy absorbed

Analysis: $Q_1 = mc\Delta T$; $Q_2 = mL_v$; $Q_{\text{total}} = Q_1 + Q_2$

Solution:

$$\begin{aligned} Q_1 &= mc\Delta T \\ &= (0.135\ \text{kg})(2.46 \times 10^3\ \text{J/(kg}\cdot{}^\circ\text{C)})(78.3\ {}^\circ\text{C} - 21.5\ {}^\circ\text{C}) \\ Q_1 &= 1.886 \times 10^4\ \text{J (one extra digit carried)} \\ Q_2 &= mL_v \\ &= (0.135\ \text{kg})(8.6 \times 10^5\ \text{J/kg}) \\ Q_2 &= 1.161 \times 10^5\ \text{J (two extra digits carried)} \\ Q_{\text{total}} &= 1.886 \times 10^4\ \text{J} + 1.161 \times 10^5\ \text{J} \\ Q_{\text{total}} &= 1.3 \times 10^5\ \text{J} \end{aligned}$$

Statement: Ethyl alcohol absorbs a total of 1.3×10^5 J of energy when a 135 g sample at 21.5 °C is heated until all of it boils and turns into vapour.

Practice

1. How much thermal energy is released when 2.0 L of liquid water freezes? T/I [ans: 6.8×10^5 J]
2. How much thermal energy is absorbed when a 350 g bar of gold melts? T/I [ans: 3.9×10^5 J]
3. How much thermal energy is released when 500 g of steam at 100 °C condenses into liquid water and then cools to 50 °C? T/I [ans: 1.3×10^6 J]

Water: A Special Liquid

Most solids sink in their respective liquids. For example, solid iron sinks in liquid iron. This occurs because the particles of the solid are more closely packed than the particles of the liquid, making the solid denser. However, water is different. Ice floats on water because water is one of the few substances whose solid is less dense than its liquid (**Figure 5**). This is based on the water molecule's chemical structure. Water molecules are V-shaped and have two hydrogen atoms attached to one oxygen atom (**Figure 6**).

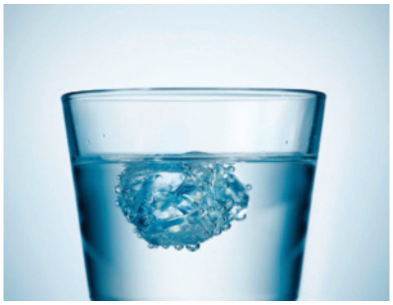


Figure 5 Most solids are more dense than their liquids. Ice, however, floats on liquid water.

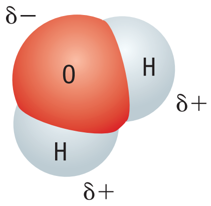


Figure 6 A water molecule has two hydrogen atoms with a slight positive charge and one oxygen atom with a slight negative charge (δ means "partial charge").

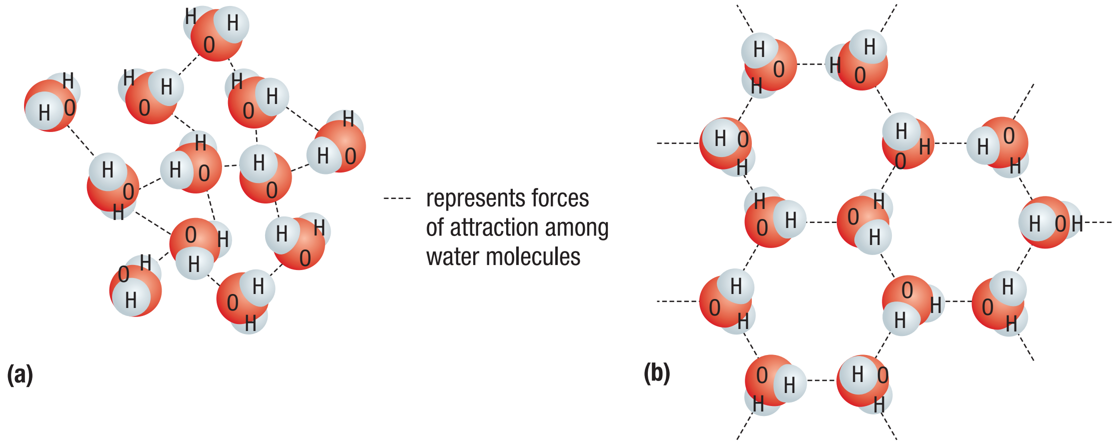


Figure 7 (a) At temperatures above 4 °C, water molecules are relatively disorganized. (b) As the temperature of the water decreases, the molecules move more slowly, forming a more organized structure, so that molecules of ice take up more space than those of liquid water.

The hydrogen atoms in a water molecule have a small positive charge, while the oxygen atom has a small negative charge. The hydrogen atoms of one water molecule are attracted to the oxygen atoms of neighbouring water molecules. This occurs because opposite charges are attracted to one another.

However, at temperatures above 4 °C, molecules of water move too fast for these forces of attraction to pull the molecules together. At these temperatures, water molecules are relatively disorganized (**Figure 7(a)**). As the temperature decreases, the molecules move slowly enough for the forces of attraction to place the molecules into a more organized structure. The more organized molecules of water in ice take up more space than the more disorganized molecules in liquid water, so water expands as it freezes (**Figure 7(b)**).

The expansion of water when it freezes can cause a lot of problems. Pipes in homes or under the street can break under the pressure of the expanding, frozen water. When the water thaws, it flows out of the broken pipes, causing flooding and damage (**Figure 8**).

Figure 8 When pipes freeze and burst, it can be a big mess, both above ground on road surfaces and below ground in water and sewer systems.

6.4 Summary

- The three states of matter are solid, liquid, and gas. When thermal energy is released or absorbed a change of state may happen.
- The change in temperature that occurs as a substance releases or absorbs thermal energy can be shown in a cooling graph or a heating graph.
- The thermal energy that is absorbed or released during a change of state is called the latent heat of the substance. If the substance is melting or freezing, it is called the latent heat of fusion. If the substance is evaporating or condensing, it is called the latent heat of vaporization.
- The specific latent heat of fusion (L_f) is the amount of thermal energy per kilogram needed to melt or freeze a substance. The specific latent heat of vaporization (L_v) is the amount of thermal energy needed per kilogram to evaporate or condense a substance.
- The equation $Q = mL_f$ is used to calculate the latent heat of fusion, and $Q = mL_v$ is used to calculate the latent heat of vaporization.
- Ice is one of the few solids that floats in its liquid; this is due to the shape of its molecules and the forces of attraction between its molecules.

6.4 Questions

1. (a) Describe each part of the graph in **Figure 9** in terms of the states of matter.
   (b) What type of graph is this, a heating graph or a cooling graph? How can you tell? K/U T/I

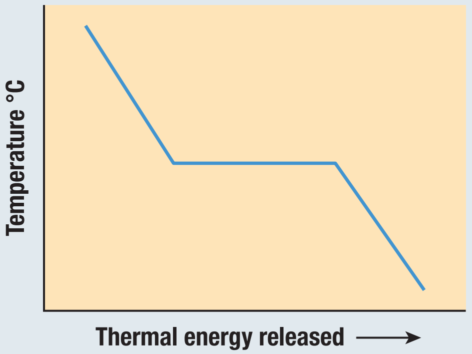


Figure 9

2. (a) Use **Table 2** to graph a heating curve.
   (b) Label the appropriate parts of the graph with the following: solid, liquid, gas, melting, evaporation.
   (c) Determine the melting point and boiling point of the substance. T/I
3. Describe what would happen if you were to heat liquid water to a temperature of 110 °C. K/U
4. Explain the terms "latent heat of fusion" and "latent heat of vaporization." K/U
5. To prevent fruit on trees from freezing and becoming inedible, fruit farmers in Ontario often spray their crops with water if they know the temperatures are going to drop below zero. Use your knowledge of latent heat to explain why this will help prevent the fruit from freezing. K/U A
6. Calculate the latent heat of fusion for 2.40 kg of gold as it changes from a molten liquid into a solid bar. T/I
7. How much thermal energy is needed to change 100 g of ice at −20 °C into steam at 110 °C? T/I
8. While forming a 1.50 kg aluminum statue, a metal smith heats the aluminum to 2700 °C, pours it into a mould, and then cools it to a room temperature of 23.0 °C. Calculate the thermal energy released by the aluminum during the process. T/I
9. What makes water different from most other substances? Include a description of the physical characteristics in your answer. K/U

Table 2 Data Collected during the Heating of a Substance

Time (min)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5
Temperature (°C)	37	43	49	55	55	55	56	64	70	80	86	90	90	90	100

6.5 Heating and Cooling Systems

Canadians require heating systems to keep homes, schools, and other buildings comfortable during the winter. Many buildings are also equipped with cooling systems for the summer. Conventional heating systems use oil or natural gas as fuels, and air conditioners typically use electricity. In some cases, electric heaters are used for heating. Scientists and engineers are developing more affordable energy-efficient alternatives that Canadians can use for their heating and cooling needs.

Conventional Heating Systems

electrical heating system a system that uses electricity to produce thermal energy for heating

forced-air heating system a system that moves hot air to heat a building

hot water heating system a system that uses hot water to heat a building

All heating systems have a source of thermal energy, a means of transferring the energy from one place to another, and a device that controls the production and distribution of energy. Conventional heating systems use either electricity or fossil fuels as a source of thermal energy. **Electrical heating systems** generate thermal energy by allowing an electric current to pass through metal wires that have a high resistance to the current that passes through them. Similar wires are used in the elements of an electric stove and a toaster. The thermal energy is transferred throughout the building by convection. Fossil fuel systems generate thermal energy by burning fossil fuels such as oil or natural gas.

Some heating systems use the thermal energy to heat air while others use the thermal energy to heat water. A **forced-air heating system** uses a furnace to warm air to heat a building (**Figure 1**). In this system, the warm air passes through ducts that eventually reach vents located in the floor or ceiling. The warm air is transferred throughout the building by convection. As warm air enters a room through the vents, colder air is pushed through another set of ducts called the cold air return, providing more air for the furnace to heat. Fresh air is also brought into the system through an intake pipe out of the building. An exhaust system releases gases such as carbon dioxide. A **hot water heating system** uses a boiler to heat water to heat a building. The boiler uses electricity or burns fossil fuels to heat the water. The hot water is then pumped through pipes that eventually reach radiators located in various rooms of the building.

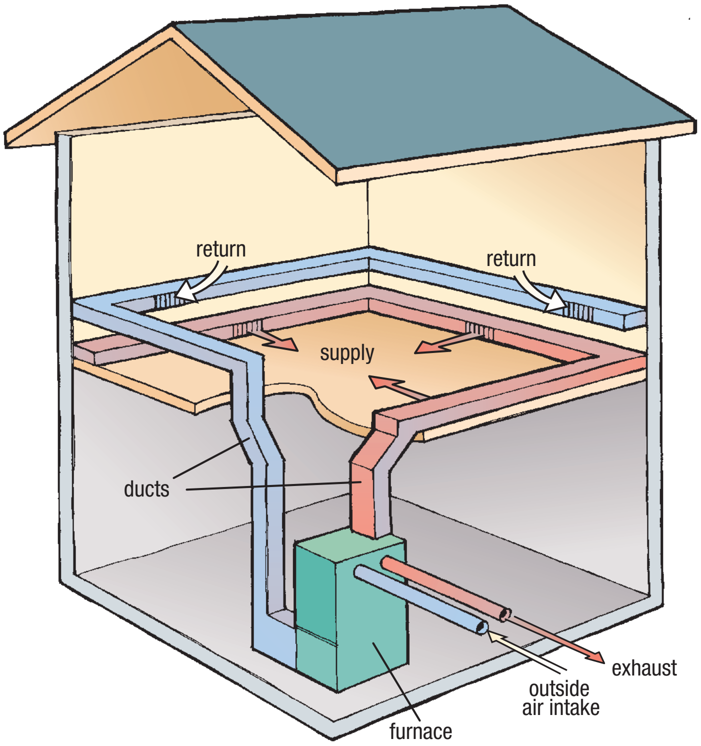


Figure 1 In a typical forced-air system, warm air from the furnace is supplied to each room through a network of ducts. A separate set of ducts returns cooler air to the furnace and brings in fresh air from outside to the furnace for heating.

Conventional Cooling Systems

The physics of conventional air conditioners, refrigerators, and freezers is very similar. All of these appliances use the evaporation of a liquid to absorb thermal energy from air. First, a compressor puts a special type of gas, called a refrigerant, under pressure. Whenever a gas is compressed, its temperature increases. The warm refrigerant gas runs through a coil of tubes, where it starts to release some of its thermal energy. As the refrigerant cools, it changes into a liquid. The liquid refrigerant then passes through an expansion valve, moving from a high-pressure area to a low-pressure area. At this point, the liquid refrigerant absorbs thermal energy from the surrounding air and evaporates back into a gas. The surrounding air cools down as a result. The compressor of an air conditioner gets very warm, so air conditioning units are installed outside the building, where the thermal energy can be released into the external environment.

In a refrigerator or freezer, the same type of compressor and coil system is used (**Figure 2**). The only difference is that the cooled air is produced in the refrigerator or freezer and the warm air is released into the external environment.

CAREER **LINK**

HVAC (heating, ventilation, air conditioning) engineers and technicians design and maintain the heating and cooling systems of buildings. To learn more,

GO TO NELSON SCIENCE

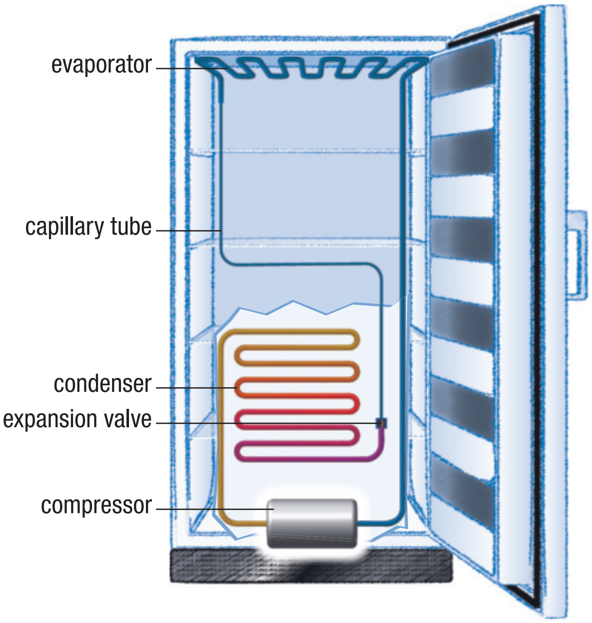


Figure 2 The compressor in a refrigerator puts the refrigerant under pressure to change it into a liquid. When the refrigerant moves through the expansion valve, the pressure decreases and the liquid evaporates as it passes through the evaporator, removing thermal energy from the air.

Controlling Heating and Cooling Systems

Both heating and cooling systems contain a thermostat to sense the temperature of the environment and turn the furnace or air conditioner on or off accordingly. Conventional thermostats contain a coiled bimetallic strip and a mercury switch (**Figure 3**). A bimetallic strip consists of two types of metal bonded together back to back. Due to the different types of metals, the two sides of the strip expand and contract at different rates when heated or cooled. Expansion and contraction make the coil tighten and loosen as the temperature of the house fluctuates. On top of the bimetallic strip is the mercury switch. Mercury is a liquid metal that flows like water and also conducts electricity. When the bimetallic strip coil changes shape again, the mercury switch tilts and the mercury moves inside. When the temperature in the building is above or below the temperature that an operator has set on the thermostat, the switch tilts in one direction and causes the mercury to touch two bare wires. This creates a closed circuit and turns the furnace or air conditioner on. As the environment warms up or cools down, the bimetallic coil changes shape again. This causes the switch to tilt in the opposite direction, moving the mercury away from the circuit wires. This opens the circuit and turns the furnace or air conditioner off.

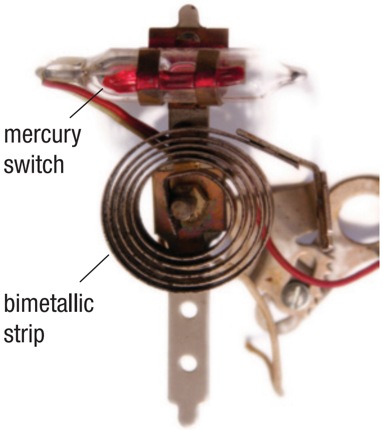


Figure 3 A bimetallic strip is curled into a coil so it winds up or unwinds as the temperature changes, resulting in the tilting of the mercury switch on the top.

Geothermal Systems: An Alternative Method of Heating and Cooling

The most popular methods of heating involve the burning of fossil fuels. This burning results in the release of greenhouse gases, such as carbon dioxide, into the atmosphere, contributing to global warming. The refrigerants used in cooling systems are also greenhouse gases and contribute to global warming when they leak into the environment. Some refrigerants also damage the ozone layer, a layer of ozone gas in the upper atmosphere that helps reduce the amount of ultraviolet radiation from the Sun that reaches Earth's surface. Damage to the ozone layer contributes to increases in skin cancer caused by excess ultraviolet radiation. To reduce production of greenhouse gases and protect the ozone layer, alternative forms of heating and cooling are being developed. Several alternatives were introduced in Chapter 5. One of the newest heating and cooling technologies makes use of the thermal energy contained within Earth's crust. **Geothermal systems** use heat pumps to transfer Earth's natural thermal energy for heating and cooling.

geothermal system a system that transfers thermal energy from under Earth's surface into a building to heat it, and transfers thermal energy from the building into the ground to cool the building

Temperatures at a depth of 3 m below the ground remain fairly steady throughout the year. Depending on the latitude, the actual ground temperature can vary. In Ottawa, the temperature remains at about 9 °C, which might seem cold, but it can still be used to heat a building in the winter.

During the winter, the temperature below the ground is higher than the temperature above the ground. In a geothermal system, a liquid antifreeze–water mixture is pumped through a network of plastic pipe that is placed a few metres underground. As the antifreeze–water mixture is pumped through the pipes, the thermal energy from the ground is transferred to the walls of the pipe by conduction and then transferred from the pipe to the liquid by convection. The liquid is then pumped into a heat pump located inside the building, which then transfers the thermal energy from the liquid to the air inside the building (**Figure 4(a)**).

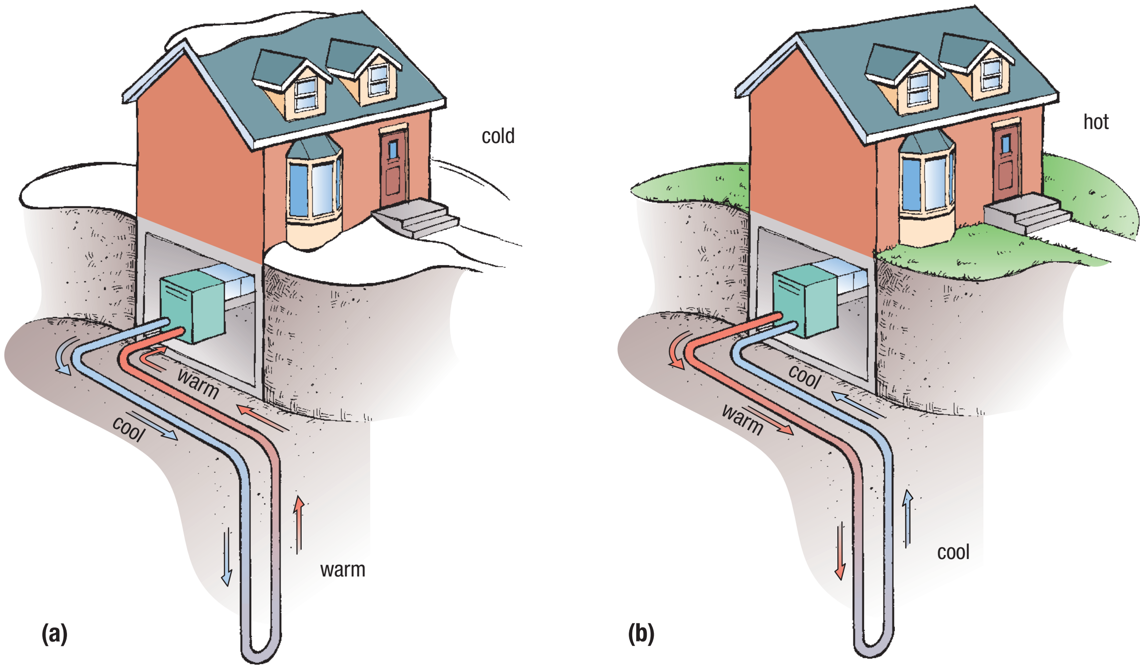


Figure 4 (a) In a geothermal system, thermal energy from below the ground is transferred to a heating system inside a building during the winter, heating the building. (b) During the summer, thermal energy is transferred from the building to the ground outside, cooling the building.

Inside the heat pump, a liquid refrigerant is pumped through a series of coils. Thermal energy is transferred from the antifreeze–water mixture to the refrigerant, changing the refrigerant into a gas. The gas moves through another set of coils where the pressure is increased. As the pressure of the gas increases, its temperature also increases. Air blows over the coils containing the hot refrigerant gas, and the hot air is distributed through ducts to warm the building.

During the summer, the heat pump process is reversed. Hot air from the house is pumped over the refrigerant, causing it to warm up. The refrigerant then transfers its thermal energy to the antifreeze–water mixture so that the mixture warms up. Since it is cooler underground than above ground during the summer, the thermal energy is transferred from the antifreeze–water mixture to the ground by conduction (**Figure 4(b)**).

6.5 Summary

- All heating systems have a source of thermal energy, a means of transferring the energy, and a thermostat to control the production and distribution of energy. Conventional heating systems use either electricity or fossil fuels as a source of thermal energy.
- Conventional cooling systems use the evaporation of pressurized refrigerants to absorb thermal energy from the air, resulting in cool air that can then be blown through a duct system.
- A typical thermostat uses a bimetallic strip and a mercury switch to turn a heating or cooling system on or off as temperatures change.
- Conventional heating and cooling systems produce greenhouse gases such as carbon dioxide, so they are not considered environmentally friendly.
- Geothermal systems use Earth's natural thermal energy for heating and cooling purposes. In the winter thermal energy is transferred from below Earth's surface into a building to heat it. In the summer, thermal energy is transferred from a building into Earth's surface to cool it.

UNIT TASK **BOOKMARK**

You can apply what you have learned about heating and cooling systems to the Unit Task on page 360.

6.5 Questions

1. Forced-air heating systems are found in most homes. Brainstorm reasons why they are so popular. K/U A
2. Refrigerants used in air conditioners and refrigerators can be a type of chlorofluorocarbon, or CFC. Research other uses for CFCs. A
3. Research programmable thermostats and smart thermostats. How do these thermostats work? Why are these thermostats environmentally friendly? A
4. Why can a geothermal system be used as both a heating system and a cooling system? K/U
5. Create a flow chart or other graphic organizer summarizing the process of heating and cooling using geothermal energy. K/U A
6. The specific heat capacity of water is much greater than that for air. T/I C A
   (a) Research the specific heat capacity value for air.
   (b) Perform research to compare the efficiency of a typical new forced-air furnace for a home with that of a new hot water boiler.
   (c) Based on your research, comment on which heating system would be more effective, a forced-air system or a hot water system.

GO TO NELSON SCIENCE

6.6 Explore an Issue in Thermal Energy

SKILLS MENU

- Defining the Issue
- Researching
- Identifying Alternatives
- Analyzing
- Defending a Decision
- Communicating
- Evaluating

Geothermal Systems: Friend or Foe?

Geothermal heating and cooling systems are becoming popular alternatives to conventional heating and cooling systems. In fact, geothermal systems are extremely popular in Sweden and other European countries. The purpose of installing a geothermal system is to heat and cool your home efficiently without causing damage to the environment. Although there is a more significant upfront cost to install, there is very little cost involved in operating and maintaining these systems. So homeowners can save, and even earn, money.

Geothermal systems are advertised to be safe and environmentally friendly because they do not use fossil fuels, so they do not release greenhouse gases. As you learned in Section 6.5, a geothermal system uses water containing antifreeze that is pumped into the ground to be warmed by the Earth. This antifreeze–water mixture is then pumped into a heat pump, which transfers the thermal energy from the liquid to the air in your home. All heat pumps use a refrigerant during the transfer of thermal energy.

During the summer, the refrigerant process is reversed in the heat pump. The antifreeze–water mixture absorbs thermal energy from a building and releases it underground, cooling the building in the process.

In cases where there is a lot of land around a building, the geothermal pipes may be laid horizontally in the ground (**Figure 1**). In cases where there is less land around a building, the pipes may be inserted vertically into pre-drilled holes in the ground. However, sometimes it is not possible to install a geothermal system in a building. Geothermal heating and cooling systems may cause pollution if refrigerants or antifreeze leak into the environment.

CAREER LINK

To learn about a career in the geothermal heating/cooling industry,

GO TO NELSON SCIENCE

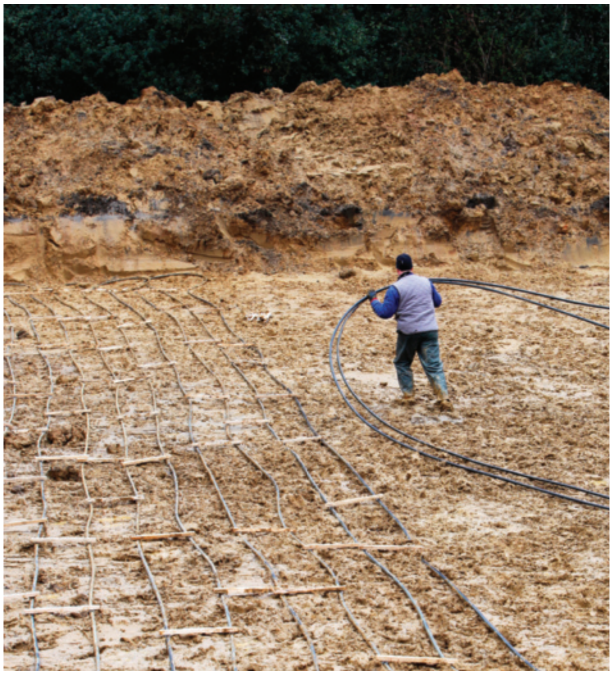


Figure 1 Pipes are buried underground to allow for the exchange of thermal energy between an antifreeze–water mixture and Earth.

The Issue

Do the benefits of geothermal systems outweigh the risks and costs?

ROLE

You will assume the role of a builder of custom houses. As a geothermal heating and cooling expert, you want to provide your customers with all of the information they need to make an informed choice.

AUDIENCE

Your clients have been asking you if they should install geothermal systems instead of conventional heating and cooling systems. They are considering this change because they are concerned about the environment and want to do their part to help. Most of the pamphlets they have read about geothermal systems make it sound like an amazing solution to our environmental problems.

You will need to communicate your findings clearly to your clients so they can understand the pros and cons of geothermal systems including the environmental and financial advantages and disadvantages.

Goal

To advise your clients on the pros and cons of geothermal heating and cooling systems so that they can decide if they should include such a system in their new home design

Research

Research the pros and cons of geothermal heating and cooling systems at the library or on the Internet. Be sure to include the dangers associated with antifreeze and refrigerants in geothermal systems. Also include information on the cost of installing the system, as this is important information for your clients.

WEB LINK

To learn more about geothermal heating and cooling systems,

GO TO NELSON SCIENCE

Identify Solutions

You might want to consider the following in your analysis:

- safety benefits associated with a geothermal system versus a fossil fuel–burning furnace; consider fuel leakage, carbon monoxide emissions, and explosions due to propane, among other factors
- environmental damage associated with producing the electricity to run the heat pump in a geothermal system
- problems with antifreeze
- environmental benefits of geothermal systems
- other environmentally friendly alternatives to geothermal systems

Make a Decision

SKILLS HANDBOOK A5.2

What would you recommend to clients who are interested in installing geothermal heating and cooling systems? Make sure that you develop clear reasons for your viewpoint by creating a risk-benefit analysis.

UNIT TASK BOOKMARK

You can apply what you have learned about geothermal systems and other alternatives to the Unit Task on page 360.

Communicate

Create a clear outline of the pros and cons of a geothermal heating and cooling system. You can present the information in the form of a pamphlet, multimedia presentation, video presentation, or web page.

Plan for Action

Create a plan for how to distribute the information you collected to local homeowners. Consider the homeowners in your community (staff, parents, and neighbours). Use resources such as the school website, school newspaper, parent newsletters, and local newspapers. Make sure that you present an unbiased view of the issue so that community members can make their own decisions on the issue. To do this, you will need to clearly outline both the pros and the cons of geothermal systems.

When a Brewer Becomes a Scientist

ABSTRACT
James Prescott Joule did not start off his career as a scientist, but through hard work and perseverance became one of the most famous physicists of his day. His goal was to determine how work, mechanical energy, and thermal energy are related. Through years of experimentation, he gathered and analyzed extensive amounts of data until his theories were finally taken seriously. The result was a dramatic change in our understanding of thermal energy.

A Scientist Is Born

James Prescott Joule (**Figure 1**) was born into a family of English brewers. Due to poor health, he was not given a formal education. Instead, he studied at home with the help of tutors until the age of 15, when he went to work in his family's brewery. His interest in science was sparked when he and his brother went to study under the famous chemist John Dalton. His studies were aimed at learning more about the brewing process, but the result was a lifelong love of science. When Joule returned home, he set up his own laboratory and started experimenting. Science became Joule's hobby—one that he was passionate about. Unfortunately, this did not make his work acceptable to other scientists at the time.

Figure 1 James Prescott Joule

Early Experiments

Joule's scientific career began when he determined the amount of thermal energy produced by an electric current. He discovered that current and resistance were directly related to the amount of thermal energy generated, a concept now referred to as Joule's law. Joule's scientific report was presented to the Royal Society of London, which was made up of some of the day's most distinguished scientists. However, the report was not met with much enthusiasm.

Undaunted, James Joule started investigating thermal energy from both electric and mechanical sources. He used electricity to warm up a volume of water so that it changed in temperature by 1 °F. He then used mechanical energy, by forcing water through a perforated cylinder, to produce friction and increase the temperature of the same amount of water by 1 °F. These investigations showed that a similar amount of energy was needed in both cases. These findings were presented to the British Association for the Advancement of Science, but again there was very little interest in his work. Joule was considered to be a wealthy brewer, not a scientist, so the scientists in the association did not take his results seriously.

Joule summarized his feelings when he said, "I shall lose no time in repeating and extending these experiments, being satisfied that the grand agents of nature are ... indestructible; and that wherever mechanical force is expended, an exact equivalent of heat is always obtained." Joule firmly believed that energy (the "grand agents of nature") was "indestructible" and that it could be changed from one form into another.

At this time, scientists believed that a fluid-like material called caloric was responsible for making objects warm or cold. When objects absorbed caloric they would become warmer, and when they lost caloric they would become colder. According to this theory, an object could become warmer only if it came into contact with a warmer object so that caloric could flow from the warmer object into the cooler object. Joule did not share this view. He thought that objects could become warmer without coming into contact with warmer objects. Joule believed that all forms of energy are the same, and that one form can be changed into another. Thus, he believed that mechanical energy or electrical energy could be transformed into thermal energy.

Finally, a Breakthrough

In a report published in a leading British physics journal in 1845, entitled "The Mechanical Equivalent of Heat," Joule described an investigation in which he used a falling mass to turn a paddlewheel placed inside an insulated barrel of water (**Figure 2**). As the paddlewheel turned, the water inside the barrel warmed up and its temperature rose. This indicated that mechanical energy could be transformed into thermal energy. Joule precisely measured the amount of mechanical energy that was needed to raise the temperature of 1 lb (0.45 kg) of water by 1 °F. This result allowed Joule to determine the amount of mechanical energy needed to generate a unit of heat (thermal energy was called "heat" at that time). Joule called this value the "mechanical equivalent of heat" since it related mechanical energy to thermal energy.

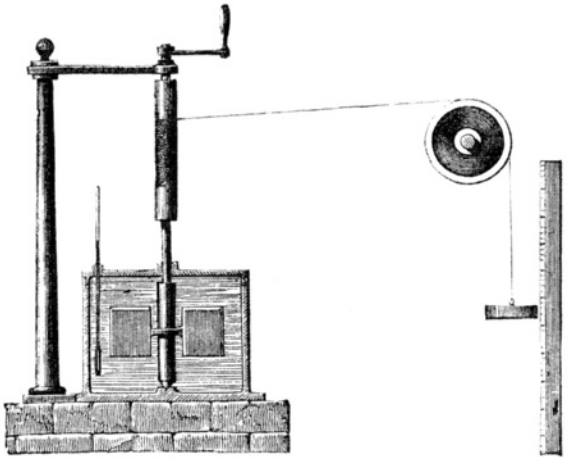


Figure 2 Joule's apparatus to measure the mechanical equivalent of heat. As the mass on the right falls, its energy is used to turn the paddlewheel inside the water in the barrel. The thermometer measures any changes in the temperature of the water.

Eventually, Joule became a highly respected scientist and was elected as a member of the Royal Society (a fellowship of the most influential scientists in the world). Many of his theories led to the development of the first law of thermodynamics, otherwise known as the law of conservation of energy. The SI unit of energy is called the joule in his honour.

Further Reading

Reynolds, O. (1892). *Memoir of James Prescott Joule* (Vol. 36). Manchester, UK: Manchester Literary and Philosophical Society.

Scoresby, W. (1887). *The scientific papers of James Prescott Joule* (Vol. 1). London: The Physical Society of London.

Steffens, H.J. (1979). *James Prescott Joule and the concept of energy*. Dawson, UK: Folkstone.

GO TO NELSON SCIENCE

6.7 Questions

1. How did Joule's discoveries change our understanding of thermal energy? K/U
2. In science, we often repeat investigations or conduct a number of related investigations and compare the results. Why is this done? How is Joule's work a good example of this? K/U T/I
3. Why was Joule's early scientific work not taken seriously? Why was his work accepted by scientists later on? K/U
4. Consider the equipment Joule used in his investigations. How would it compare to equipment used today? T/I

CHAPTER 6 Investigations

Investigation 6.3.1 OBSERVATIONAL STUDY

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Specific Heat Capacity of Brass

In Section 6.3, you learned that the quantity of heat can be calculated using the equation $Q = mc\Delta T$. Different substances absorb thermal energy differently due to their specific chemical properties. This can be seen in the differing specific heat capacities of various materials.

When a warmer object is in contact with a cooler object, thermal energy moves from the warmer object to the cooler object until the temperature of both objects reaches a new value. The quantity of heat released by the warmer object is equal in magnitude to the quantity of heat absorbed by the cooler object, so $Q_{\text{released}} + Q_{\text{absorbed}} = 0$.

Purpose

To determine the experimental quantities of heat transfer and specific heat capacity in a laboratory situation

Equipment and Materials

- eye protection
- graduated cylinder
- thermometer
- stirring rod
- 250 mL beaker
- retort stand
- ring clamp
- hot plate
- 100 g brass object
- tongs
- 2 Styrofoam cups
- a balance

Procedure

SKILLS HANDBOOK A1.2, A2.4

Part A: Determining Heat Exchange

1. Put on your eye protection.
2. Use a graduated cylinder to measure 100 mL of cold tap water and place it in a Styrofoam cup. Measure and record the temperature of the cold water in a copy of **Table 1**.
3. Measure 100 mL of hot tap water and place it in a separate Styrofoam cup. Measure and record the temperature of the hot water in Table 1.
4. Pour the cold water into the hot water. Put the thermometer in the cup and use the stirring rod to mix the water. Watch the temperature carefully and record the highest temperature reached in Table 1.

Table 1 Determining Heat Exchange

	Temperature (°C)
cold water	
hot water	
mixed water	

5. Use the equations $Q = mc\Delta T$ and $Q_{\text{released}} + Q_{\text{absorbed}} = 0$ to calculate the final temperature of the mixed water.
6. Use the percentage difference equation to determine the difference between the measured value and the calculated value:

$$\%\text{ difference} = \frac{\text{measured value} - \text{calculated value}}{\text{measured value}} \times 100\ \%$$

Part B: Determining the Specific Heat Capacity of Brass

7. Place the hot plate on a retort stand with a ring clamp. The ring clamp should be positioned so that the top of the beaker is held in place by the ring.
8. Fill the 250 mL beaker one-third full with tap water. Place it inside the ring over the hot plate.
9. Use the balance to measure the mass of the 100 g brass object and record the mass in a copy of **Table 2**.

Table 2 Data for Specific Heat Capacity of Brass

	Water	Brass
mass (kg)		
initial temperature (°C)		
final temperature (°C)		

10. Place the brass object in the beaker of water on the hot plate. Turn on the hot plate and let the water come to a boil.

Be careful not to touch any hot pieces of equipment. Never touch the hot plate when it is on. When you plug the hot plate into the electrical socket, make sure everything is dry. Unplug the hot plate by pulling the plug, not the cord.

11. While waiting, measure 100 mL of cold tap water using a graduated cylinder. Put the cold water into a Styrofoam cup and take its temperature. Record this value.
12. Once the water on the hot plate boils, use the thermometer to measure its temperature. Assume that the temperature of the brass is equal to the temperature of the boiling water. This is the initial temperature of the brass. Turn off the hot plate.
13. Using a pair of tongs, remove the brass object from the boiling water and put it in the Styrofoam cup containing the cold water.
14. Gently stir the water surrounding the brass object with a stirring rod and take its temperature with a thermometer. Record the highest temperature reached.
15. Use $Q = mc\Delta T$ and $Q_{\text{released}} + Q_{\text{absorbed}} = 0$ to calculate the specific heat capacity of brass. This is the measured value for the specific heat capacity of brass.
16. The accepted value for the specific heat capacity of brass is 3.8×10^2 J/(kg•°C). Determine the percentage error for the calculation using the percentage error equation:

$$\%\text{ error} = \frac{\text{accepted value} - \text{measured value}}{\text{accepted value}} \times 100\ \%$$

17. Clean up and return all of the equipment. Remember that the hot plate will remain hot for a long time after it is turned off.

Analyze and Evaluate

(a) Consider the percentage difference obtained in Part A. What might have caused this percentage difference? T/I

(b) Consider the percentage error obtained in Part B. What may be responsible for the difference in the values between Part A and Part B? T/I

Apply and Extend

(c) This investigation shows a simple method of determining the specific heat capacity of a substance. Scientists often need to determine the specific heat capacity of unknown substances. Why would this be valuable to a scientist? A

(d) Explain what a high specific heat capacity tells you about a substance. State some uses of substances with high specific heat capacities. What are some uses for substances with low specific heat capacities? K/U A

Investigation 6.4.1 OBSERVATIONAL STUDY

Heating Graph of Water

When a substance cools down or warms up, a specific pattern of temperature changes occurs. During a change of state, the temperature remains constant. While a substance is melting, the absorbed thermal energy is transformed into a change in the potential energy of the particles, not their kinetic energy. As a substance cools and freezes, the thermal energy that is released also is transformed into a change in the particles' potential energy, not their kinetic energy. In this investigation, you will observe the pattern of temperature changes for water as it warms up.

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Purpose

To determine the temperature changes that occur as ice changes to water and to create a heating graph of water

Equipment and Materials

- hot plate
- retort stand
- ring clamp
- thermometer clamp
- thermometer
- 500 mL beaker
- stopwatch or timer
- stirring rod
- crushed ice

Procedure

1. Read through this Procedure and create a table suitable for collecting the data in the investigation.
2. Place the hot plate on a retort stand with a ring clamp and a thermometer clamp. Turn the iron ring until it is over the hot plate.
3. Fill the beaker two-thirds full with crushed ice. Place it inside the ring over the hot plate.
4. Place a thermometer in the thermometer clamp and immerse the thermometer in the crushed ice until the thermometer bulb is 1 cm to 2 cm above the bottom of the beaker.
5. Turn the hot plate on to the high setting.

Be careful not to touch any hot pieces of equipment. Never touch the hot plate when it is on. When you plug the hot plate into the electrical socket, make sure everything is dry. Unplug the hot plate by pulling the plug, not the cord.

6. Take the temperature of the ice–water mixture every 15 s, using a stirring rod to stir between measurements. Record these values in your data table.
7. In your data table, note the temperature at which you first notice the ice melting into liquid water, the temperature at which the last crystal of ice melts into liquid water, and the temperature at which the liquid water begins to boil.
8. Stop taking measurements when the water has boiled for approximately 1 min.
9. Clean up all of the equipment and return it to where you found it. Be careful with the hot plate as it will remain hot for a long time after it has been turned off.
10. Create a temperature–time graph for the data. In your graph, label the various regions of the graph (as in Figure 4 on page 290) and the three points noted in Step 7.

Analyze and Evaluate

(a) What variables were measured in this investigation? K/U

(b) Compare your heating graph of water with the heating graph in Figure 4 on page 290. Describe any similarities and differences. Suggest reasons for any differences you noticed. T/I

(c) Use the kinetic molecular theory to describe what was happening to the water molecules in the different regions of the graph. K/U

(d) Use your graph to determine the melting point of water. Why might this measured value differ from the accepted value of 0 °C? T/I

(e) Use your graph to determine the boiling point of water. Why might this value differ from the accepted value of 100 °C? T/I

(f) Suggest sources of error for this investigation. How might these sources of error be avoided? T/I

Apply and Extend

(g) Thermal pollution is caused when hot water from a electrical generating station is discharged into a body of water such as a river, lake, or ocean. Research the effects of hot water from a power plant mixing with a colder body of water. What effect might this have on the natural environment and what can be done to minimize these effects? T/I A

GO TO NELSON SCIENCE

Investigation 6.4.2 OBSERVATIONAL STUDY

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Specific Latent Heat of Fusion for Ice

The latent heat of fusion is the amount of thermal energy required for a substance to melt or freeze. The amount of thermal energy required is specific to a substance because of its individual chemical properties. In this investigation, you will determine the latent heat of fusion for melting ice.

Purpose

To determine the specific latent heat of fusion for ice

Equipment and Materials

- electronic balance
- thermometer
- stirring rod
- Styrofoam cup
- ice cubes
- a balance

Procedure

SKILLS HANDBOOK A1.2, A2.4

1. Determine the mass of the empty Styrofoam cup using the balance. Record this value in a copy of **Table 1**.

Table 1 Data to Determine the Latent Heat of Fusion of Ice

Mass of Styrofoam cup (kg)	
Mass of Styrofoam cup and hot water (kg)	
Mass of hot water (kg)	
Initial temperature of hot water (°C)	
Final temperature of water (°C)	
Final mass of Styrofoam cup and water (kg)	
Mass of ice (kg)	

2. Fill the Styrofoam cup half full with hot tap water. Measure and record the mass of the cup and hot water.
3. Calculate and record the mass of the hot water.
4. Use the thermometer to measure the initial temperature of the hot water. Record this value.
5. Immediately add four ice cubes to the water. Stir the mixture with a stirring rod until the ice completely melts.
6. As soon as the last piece of ice melts, record the temperature of the water. This is the final temperature of the water.
7. Place the Styrofoam cup back on the balance and determine the final mass. Calculate and record the mass of the ice.
8. Calculate the amount of thermal energy transferred from the hot water to the ice using the equation $Q = mc\Delta T$.
9. The amount of thermal energy transferred by the hot water (Q) is equal to the amount of thermal energy absorbed by the ice. Use the value calculated in Step 8 and the equation $Q = mL_f$ to calculate the specific latent heat of fusion for ice.
10. The known value for the specific latent heat of fusion of ice is 3.4×10^5 J/kg. Determine the percentage error using the equation

$$\% \text{ error} = \frac{\text{accepted value} - \text{calculated value}}{\text{accepted value}} \times 100\ \%$$

Analyze and Evaluate

(a) In Step 6, why was the temperature of the water measured at a point when the last piece of ice melted, and not later than that? T/I

(b) Suggest sources of error for this investigation. How might these sources of error be avoided? T/I

Apply and Extend

(c) Cities like Toronto that are near large bodies of water that freeze in the winter experience cooler springs and warmer winters than cities that are not near large bodies of water. How does the latent heat of fusion of water help explain this cooling and warming effect? A

CHAPTER 6 SUMMARY

Summary Questions

1. Create a study guide based on the points in the margin on page 268. For each point, create three or four subpoints that provide further information, relevant examples, explanatory diagrams, or general equations.
2. Look back at the Starting Points questions on page 268. Answer these questions using what you have learned in this chapter. Compare your latest answers with those that you wrote at the beginning of the chapter. How has your understanding changed during the study of this chapter? Note how your answers have changed.

Vocabulary

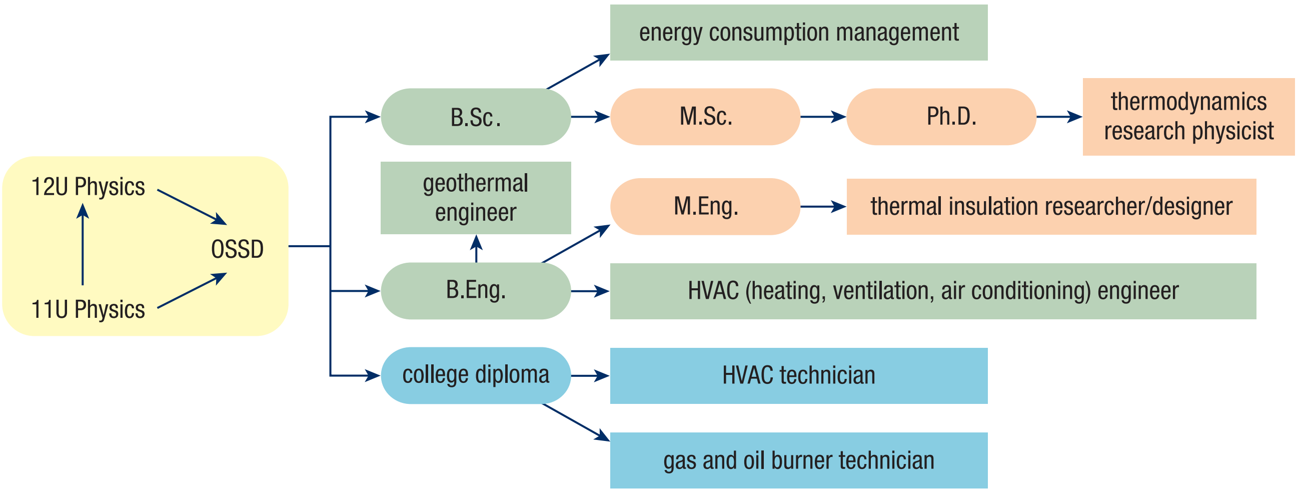
kinetic molecular theory (p. 270)
thermal energy (p. 271)
temperature (p. 271)
Celsius scale (p. 272)
Fahrenheit scale (p. 272)
Kelvin scale (p. 272)
melting point (p. 274)
freezing point (p. 274)
boiling point (p. 274)
condensation point (p. 274)
heat (p. 276)
thermal conduction (p. 276)
convection (p. 277)
convection current (p. 277)
radiation (p. 278)
thermal conductor (p. 279)
thermal insulator (p. 279)
specific heat capacity (c) (p. 281)
quantity of heat (Q) (p. 281)
principle of thermal energy exchange (p. 283)
thermal expansion (p. 286)
thermal contraction (p. 287)
fusion (p. 289)
heating graph (p. 290)
cooling graph (p. 290)
latent heat (Q) (p. 291)
latent heat of fusion (p. 291)
latent heat of vaporization (p. 291)
specific latent heat (L) (p. 291)
specific latent heat of fusion (L_f) (p. 291)
specific latent heat of vaporization (L_v) (p. 291)
electrical heating system (p. 296)
forced-air heating system (p. 296)
hot water heating system (p. 296)
geothermal system (p. 298)

CAREER PATHWAYS

SKILLS HANDBOOK A7

Grade 11 Physics can lead to a wide range of careers. Some require a college diploma or a B.Sc. degree. Others require specialized or post-graduate degrees. This graphic organizer shows a few pathways to careers related to topics covered in this chapter.

1. Select an interesting career that relates to Thermal Energy. Research the educational pathway you would need to follow to pursue this career.
2. What is involved in becoming a geothermal engineer? Research at least two pathways that could lead to this career, and prepare a brief report of your findings.



12U Physics
11U Physics
OSSD
B.Sc.
B.Eng.
college diploma
geothermal engineer
energy consumption management
M.Sc.
Ph.D.
thermodynamics research physicist
M.Eng.
thermal insulation researcher/designer
HVAC (heating, ventilation, air conditioning) engineer
HVAC technician
gas and oil burner technician

GO TO NELSON SCIENCE

CHAPTER 6 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. In the past, scientists believed that warmth and coldness were produced by a massless fluid called
   (a) caloric
   (b) thermal energy
   (c) kinetic energy
   (d) kelvin (6.1) K/U
2. Which of these shows the states of water ranked according to increasing amounts of thermal energy? (6.1) K/U
   (a) water vapour, liquid water, ice
   (b) ice, liquid water, water vapour
   (c) liquid water, water vapour, ice
   (d) ice, water vapour, liquid water
3. What process is taking place when a cooler, denser gas pushes up a warmer, less dense gas? (6.2) K/U
   (a) radiation
   (b) conduction
   (c) condensation
   (d) convection
4. Which of these is a good conductor of thermal energy? (6.2) K/U
   (a) plastic
   (b) copper
   (c) animal fur
   (d) fibreglass
5. The specific heat capacity of an object depends on
   (a) the material from which the object is made
   (b) the shape of the object
   (c) the temperature of the object
   (d) the mass of the object (6.3) K/U
6. Two different liquids at different temperatures are mixed in a thermally insulated container. The final temperature of the mixture will depend on
   (a) the mass of each liquid
   (b) the initial temperature of each liquid
   (c) the specific heat capacity of each liquid
   (d) all of the above (6.4) T/I
7. The amount of thermal energy needed to change 1 kg of ethyl alcohol from a liquid to a gas is its
   (a) specific heat capacity
   (b) specific latent heat of fusion
   (c) specific latent heat of vaporization
   (d) kinetic energy (6.4) K/U
8. Which of these operations of a conventional cooling system directly results in cooling of the surrounding air? (6.5) T/I
   (a) A gas refrigerant warms up.
   (b) A gas refrigerant is compressed.
   (c) A liquid refrigerant absorbs thermal energy from the surrounding air and evaporates.
   (d) A warm gas refrigerant runs through a coil of tubes and releases thermal energy.
9. James Joule believed that
   (a) the law of conservation of energy was flawed
   (b) a massless fluid was responsible for making objects warm and cold
   (c) energy was destructible
   (d) mechanical energy and electrical energy could be changed into thermal energy (6.7) K/U

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

10. The kinetic molecular theory describes particles of matter as being motionless due to the kinetic energy that they possess. (6.1) K/U
11. A unit of measure on the Kelvin temperature scale is larger than a unit of measure on the Celsius temperature scale. (6.1) K/U
12. A 10 kg block of cedar possesses a different amount of total kinetic energy than a 15 kg block of cedar at the same temperature. (6.2) T/I
13. Substances that readily allow the transfer of thermal energy make good thermal insulators. (6.2) K/U
14. Thermal expansion occurs when substances cool down and decrease in volume as their particles lose energy. (6.3) K/U
15. Water is unlike most substances in that its solid floats on its respective liquid. (6.4) K/U
16. During the time period in which a liquid freezes to a solid, its temperature remains constant. (6.4) K/U
17. The two types of metals on the bimetallic strip of a thermostat cause the sides of the strip to expand and contract at different rates. (6.5) K/U
18. In a geothermal cooling system, thermal energy is transferred from an antifreeze–water mixture and then into the ground by conduction. (6.5, 6.6) K/U A
19. The SI unit for electric current is named after James Joule. (6.7) K/U

To do an online self-quiz,
GO TO NELSON SCIENCE

CHAPTER 6 REVIEW

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

Knowledge

For each question, select the best answer from the four alternatives.

1. The total amount of kinetic energy and potential energy possessed by the particles of a substance is its
   (a) heat
   (b) temperature
   (c) kelvins
   (d) thermal energy (6.1) K/U
2. −273 °C is known as
   (a) the freezing point
   (b) absolute zero
   (c) heat capacity
   (d) specific latent heat (6.1) K/U
3. At 646 m above sea level, water boils at 97.9 °C. What is this temperature in kelvins? (6.1) K/U
   (a) −175 K (c) 212 K
   (b) 0 K (d) 371 K
4. The type of thermal energy transfer that can occur in solids, liquids, and gases is
   (a) radiation
   (b) conduction
   (c) convection
   (d) all of the above (6.2) K/U
5. The amount of energy that must be added to a substance to raise 1.0 kg of the substance by 1 °C is the substance's
   (a) temperature
   (b) thermal energy
   (c) specific heat capacity
   (d) kinetic energy (6.3) K/U
6. Which type of field loop would be best for the installation of a geothermal heating/cooling system for a townhouse with a very small yard? (6.5) K/U A
   (a) a vertical loop
   (b) a horizontal loop
   (c) a pond loop
   (d) a Slinky loop
7. What is one of the environmental issues involved with geothermal systems? (6.6) K/U
   (a) Geothermal heating can leak refrigerants.
   (b) Geothermal heating burns fossil fuels.
   (c) Geothermal heating releases greenhouse gases.
   (d) Geothermal heating can use up all of the heat in the ground.
8. The SI unit of energy is named after which scientist? (6.7) K/U
   (a) Isaac Newton
   (b) Lord Kelvin
   (c) John Dalton
   (d) James Joule

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

9. It takes more energy to increase the temperature of 1.0 kg of iron by 1 °C than it takes to increase the temperature of 1 kg of water by 1 °C. (6.3) K/U
10. The quantity of heat may be positive or negative. (6.3) K/U
11. In a liquid, the particles vibrate, but they cannot easily slide past each other or move from place to place. (6.4) K/U
12. The change of state from a solid to a liquid is called fusion. (6.4) K/U
13. All air conditioners, refrigerators, and freezers use the condensation of a liquid to absorb thermal energy from the air. (6.5) K/U
14. Geothermal systems use heat pumps to transfer Earth's natural thermal energy for heating and cooling. (6.5, 6.6) K/U
15. James Joule discovered that current and resistance were directly related to the amount of thermal energy generated. (6.7) K/U

Match each term on the left with the most appropriate description on the right.

16. (a)	James Joule	(i)	created a temperature scale based on the freezing and boiling points of water
(b)	Benjamin Thompson	(ii)	showed that mechanical energy could be changed into thermal energy
(c)	Anders Celsius	(iii)	conducted drilling investigations showing caloric does not exist
(d)	William Thomson	(iv)	created a temperature scale based on a substance's total thermal energy (6.1, 6.7) K/U

Write a short answer to each question.

17. Give three examples of warmth and coldness found in everyday life that can be used to disprove the caloric theory. (6.1) T/I A
18. What is the equation for quantity of heat? (6.3) K/U
19. What physical state is water in when its temperature is 112 °C? (6.4) K/U
20. What was Joule's initial work and what did he begin studying that led him toward a fascination with science? (6.7) K/U
21. How does mixing a substance change its temperature? (6.1, 6.7) K/U

Understanding

22. (a) Describe the theory that scientists used to explain warmth and coldness during the eighteenth century.
    (b) How was this theory disproved? (6.1) T/I C
23. Describe the differences in particle placement and motion in solids, liquids, and gases. (6.1) K/U
24. (a) Describe the changes that occur when you place an alcohol or mercury thermometer into a warm substance and the temperature reading on the thermometer rises.
    (b) Using your understanding from (a), describe what happens when an alcohol or mercury thermometer is placed in a cool substance and the temperature reading drops. (6.1) K/U
25. Three different temperature scales are used in the world today. Describe each scale, including any significant numbers on the scale. (6.1) K/U
26. Object A and object B are each heated until they increase in temperature by the same amount. Explain how there can be more thermal energy transferred during the heating process to object A than to object B. (6.2) T/I
27. Explain the difference between how the word “heat” is used in common language and how it is used in scientific language. (6.2) K/U
28. For each scenario, describe how thermal energy is being transferred. (6.2) K/U
    (a) A spoon is used to stir a hot cup of tea and afterward becomes warm.
    (b) Earth receives thermal energy from the Sun.
    (c) The handle of a large metal spoon becomes hot when the ladle is left inside a cooking pot.
    (d) During the summer, the second floor of a house becomes warmer than the first floor.
29. A metal ball can pass through a metal ring. When the ball is heated, however, it gets stuck in the ring. What would happen if the ring, rather than the ball, were heated? Describe what is happening in both situations. (6.2) K/U
30. Explain why your finger sticks to a metal ice tray that has just come out of the freezer. (6.2, 6.3) K/U A
31. Explain what specific heat capacity is. What does it mean for an object to have a large specific heat capacity? What does it mean if the specific heat capacity is small? (6.3) K/U
32. State whether you would want to make each item from a material that has a large specific heat capacity or a small specific heat capacity and why. (6.3) K/U C A
    (a) the wire filaments in a toaster
    (b) the insulation for electric wires
    (c) the handles for cookware
    (d) the part of cookware that is in contact with the stove
33. Find the amount of thermal energy lost when 300.0 g of aluminum cools from 120 °C to 55 °C. (6.3) T/I
34. A 50.0 g sample of lead starts at 22 °C and is heated until it absorbs 8.7×10^2 J of energy. Find the final temperature of the lead. (6.3) T/I
35. As a block of glass is heated, its temperature changes from 28 °C to 440 °C as it absorbs 1.2 × 106 J of energy. Find the mass of the glass block. (6.3) T/I
36. Silver is melted and then poured into a mould to make a ring. (6.3, 6.4) K/U C
    (a) Describe what happens to the thermal energy as the silver cools.
    (b) Name the process(es) taking place as the silver cools.
37. (a) What is the symbol for quantity of heat and latent heat?
    (b) Why is the symbol the same for both quantities? (6.3, 6.4) K/U
38. The heating graph in **Figure 1** shows the change in temperature of a liquid over time. Describe the changes that are taking place in the liquid as it increases in thermal energy. (6.4) K/U C

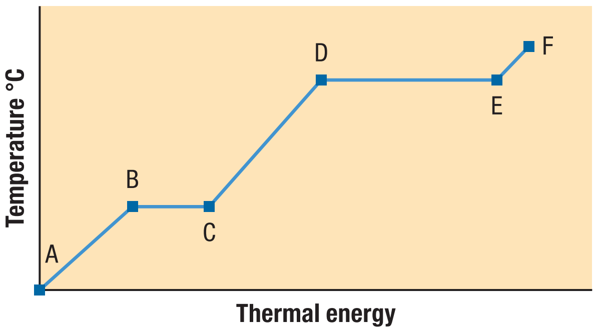


Figure 1

39. How does the kinetic and potential energy of a substance change when it melts, boils, condenses, and freezes? (6.4) K/U C

40. How much thermal energy is released when 275 g of ethyl alcohol condenses from a gas to a liquid? (6.4) K/U C

41. When 2.1×10^3 J of thermal energy is added to 0.10 kg of a substance, its temperature increases from 19 °C to 44 °C. Use **Table 1** to identify the substance. (6.4) K/U C

Table 1 Specific Heat Capacities of Common Substances

Substance	Specific heat capacity (J/(kg·°C))
water	4.18×10^3
ethyl alcohol	2.46×10^3
ice	2.1×10^3
aluminum	9.2×10^2
glass	8.4×10^2
iron	4.5×10^2
copper	3.8×10^2
silver	2.4×10^2
lead	1.3×10^2

42. (a) What common substance behaves differently from most others in its solid state?
    (b) Describe the behaviour of this substance when it is in its liquid state. (6.4) K/U

43. Describe the role that thermal energy plays when it is added or removed during a change of state. (6.4) K/U

44. A block of molten lead loses 2.1×10^4 J of thermal energy as it changes to a solid. What is the mass of the lead? (6.4) T/I

45. A sample of ethyl alcohol absorbs 6.0×10^4 J of thermal energy as it boils and completely evaporates. What is the volume of the ethyl alcohol? (6.4) T/I

46. Almost all coolant systems work in the same way. Describe how these systems work and what happens to the excess thermal energy that is not wanted. (6.5) K/U

47. (a) What characteristic of metals that causes problems in other engineering applications is essential to the functioning of a thermostat?
    (b) In your own words, explain how a thermostat works. (6.5) K/U C

48. One of the newest methods of heating and cooling is a geothermal system, which uses energy from the ground to maintain the temperature of a house. Briefly describe how this system works and how it can be used for both heating and cooling. (6.5) K/U

49. (a) Describe Joule's early experiments investigating thermal energy. What did he find and what conclusion did he come to about the "grand agents of nature"?
    (b) How were Joule's early experiments viewed by the British Association for the Advancement of Science?
    (c) Describe the breakthrough experiment Joule performed that brought him recognition from the science community. (6.7) K/U C

Analysis and Application

50. Why is temperature defined in terms of average kinetic energy, as opposed to total kinetic energy? (6.1) K/U C A

51. A drop of water and a drop of liquid with a lower boiling point than water are each placed on your skin. Which feels cooler than the other, and why? (6.1) K/U

52. A cotton ball dipped in alcohol is wiped across a counter. Explain how a change in temperature of the counter would make the smell of the alcohol more noticeable. (6.2) K/U C A

53. A pinch of orange-coloured drink mix crystals is added to a glass of cold water; another pinch of the crystals is added to the same amount of hot water. (6.1, 6.2, 6.3) T/I C
    (a) If neither is stirred, which water–crystal mixture would be the first to become uniform in colour from the dye in the crystals?
    (b) Explain your answer to (a) using the kinetic molecular theory, including one method of thermal energy transfer.

54. Wind chill is the term for the cooling effect of wind. Using the concept of heat transfer, explain why you feel colder on a windy day than on a calm day with the same high temperature. (6.2) T/I C A

55. Much like visible light, thermal radiation is transferred through waves. Although our eyes are not adapted to see this size of wavelength, its effects can still be felt through our skin. (6.2) K/U A
    (a) Name one type of animal that is able to "see" thermal radiation. How does this help it?
    (b) Give an example of how humans have used this ability in technology.

56. The reservoir of a car's radiator contains 40 mL of water. Explain how the thermal energy of the water could be changed without changing the temperature of the water. (6.4) T/I A

57. Explain why a firewalker can walk safely across red-hot coals. (6.2) K/U A

58. There is a mistake in **Figure 2.** Copy the image and correct the mistake. (6.2) K/U

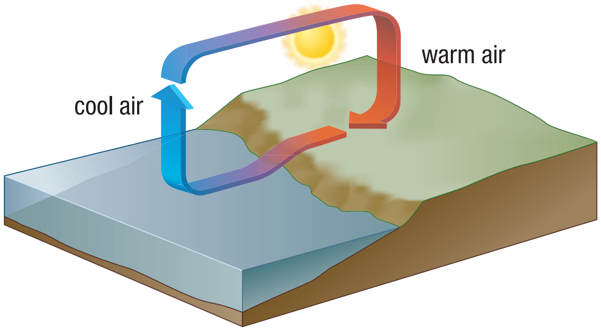


Figure 2

59. (a) Which would keep a person warmer in cold weather, a raincoat with a smooth lining, or a raincoat with a fuzzy fleece lining?
    (b) Explain how your choice in (a) keeps you warm. (6.2) K/U T/I A

60. Some structures with solar energy heating systems use bins of rocks to keep the interior warm at night. Use the principle of thermal energy exchange to explain how this setup works. (6.2) T/I A

61. Give an example of a process in which no thermal energy is transferred into or out of the system but the temperature of the system changes. (6.2, 6.3) T/I A

62. Sweating is a process that helps to cool down the body. Taking into account the concept of heat transfer, describe how rubbing oil (such as suntan oil) into the skin can inhibit this cooling process. (6.2, 6.3) T/I A

63. (a) What is the change in thermal energy when 3 L of water is heated from 18 °C to 60 °C?
    (b) During this process, is thermal energy absorbed or released by the water?
    (c) What indicates whether energy is absorbed or released during thermal energy transfer? (6.3) K/U T/I

64. One application for materials scientists is trying to create cheap, environmentally friendly substances with a large specific heat capacity. Many of these substances are actually used to help keep things cool. Explain why it is desirable for cold packs, such as those used for sports injuries and those used in coolers, to have a large specific heat capacity. (6.3) K/U C A

65. Four 5 kg blocks of the following metals sit in a room at room temperature: iron, copper, aluminum, and silver. The blocks are transferred to a room that has been heated to 30 °C. Explain in what order the blocks will heat up to 30 °C. You may refer to Table 1 in Question 41. (6.3) T/I A

66. A 3.8 kg sample of an unknown metal is heated to 396 °C and then submerged in 1.0 L of 22 °C water. The final temperature of the metal and water bath is 89 °C. Determine the unknown substance. You may refer to Table 1 in Question 41. (6.3) T/I

67. A copper wire that has been heated to 520 °C for pliability is plunged into 350 mL of water at 18 °C. The final temperature of the copper and water bath is 31 °C. Find the mass of the copper wire. (6.3) T/I

68. Dental patients can resume eating hot and cold foods and drinks soon after they have cavities replaced with fillings. Taking into account thermal expansion, what do dentists have to consider when they choose materials to use in fillings? (6.3) T/I A

69. Temperature is a measure of the average kinetic energy of all the molecules in a substance. This means that some molecules are moving more quickly than this average and some are moving more slowly. (6.1, 6.4) K/U C
    (a) If you wanted to lower the temperature of a substance, would you remove the faster molecules or the slower ones?
    (b) When water gets hot but does not boil, steam can be seen coming off it. Use your knowledge of kinetic molecular theory and phase changes to explain what is happening.
    (c) When you blow on hot water or food, the kinetic energy of the air you blow is transferred to this substance. Use the answers from (a) and (b) to explain how this helps cool down water or food.

70. Explain why a thermometer whose internal reservoir is filled with coloured water is or is not a good alternative to a mercury thermometer. (6.1, 6.3, 6.4) T/I C A

71. Jars that have been in the fridge are sometimes hard to open. Use the knowledge you have gained in this chapter to explain how running the lid under hot water helps to make opening it easier. (6.3, 6.4) K/U A

72. As opposed to using your bare finger, it is generally safer to run your finger under cool water before lightly touching it to a heating iron to determine how hot it is. (Note: never touch the element of a hot iron.) Explain this phenomenon using the concept of latent heat. (6.4) T/I C A

73. Water is a special substance because when it becomes solid it is less dense than its liquid form. This enables ice to float and life to survive on this planet. (6.4) T/I
    (a) What happens to lakes, rivers, and the polar oceans during the winter months? How does aquatic life survive during this time?
    (b) What would happen if ice sank? How would this affect aquatic plant life? How would this affect aquatic animal life?
74. (a) Use the data in **Table 2** to graph a heating curve for an unknown substance.
    (b) Label the graph with the following: solid, liquid, gas, condensing, freezing.
    (c) Determine the melting point and boiling point of the unknown substance. (6.4) T/I A

Table 2 Time and Temperature Data

Time (min)	Temperature (°C)	Time (min)	Temperature (°C)
0.5	101	5.0	36
1.0	96	5.5	24
1.5	96	6.0	12
2.0	96	6.5	0
2.5	96	7.0	−12
3.0	84	7.5	−12
3.5	72	8.0	−12
4.0	60	8.5	−26
4.5	48		

75. Conventional cooling systems rely on the heating of a refrigerant by pressure. Describe how the development of conventional cooling systems might have differed if the caloric theory had not been disproved. (6.1, 6.5) T/I C A
76. In this chapter, you learned that the temperature of a substance is caused by the kinetic energy of its molecules. Similarly, if you have a gas stored in a container, such as a balloon or a compression tank, the pressure on the tank is caused by the air molecules bumping into the sides of the container. **Figure 3** shows a gas confined in a cylinder. Use your knowledge of the kinetic molecular theory to answer the following questions: (6.1, 6.5) T/I A
    (a) If the disc below the gas is mechanically forced downward and no gas escapes, what happens to the pressure of the gas?
    (b) If the disc is forced upward how does the pressure of the gas change?
    (c) The disc is constantly being hit by gas molecules. When it is mechanically forced downward what happens to the kinetic energy of these molecules? How does this affect the temperature of the gas?
    (d) Similarly, how does raising the disc affect the kinetic energy of the molecules and the temperature of the gas?

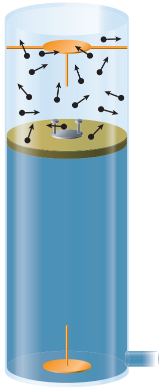


Figure 3

77. Explain why the stream in an underground cave does not freeze during the winter, when outside temperatures can reach −25 °C. (6.5) T/I A
78. Two types of field loops used in geothermal heating and cooling systems were introduced in this chapter. Describe what other factors, aside from the amount of ground space and type of terrain, might require consideration when choosing the type of field loop to use in a geothermal system. (6.6) T/I A
79. (a) In your own words, describe James Joule's experiments and measurements leading to what he called the "mechanical equivalent of heat."
    (b) How was the outcome of Joule's investigations related to that of Benjamin Thompson's investigations involving iron cylinders? (6.7) T/I C A

Evaluation

80. Newton used a thermometer filled with linseed oil on which the melting point of ice was 0 N, and body temperature was 12 N. Evaluate the advantages and disadvantages of Newton's scale. (6.1) T/I A
81. Both heat conduction and wave propagation involve the transfer of energy. Is there any difference in the principle behind these two phenomena? (6.2) T/I A
82. What requirements for thermal conductivity, specific heat capacity, and coefficient of expansion would you want in a material that is to be used to make cooking utensils? (6.2, 6.3, 6.4) T/I A

83. The use of geothermal energy for heating and cooling systems is a relatively new technology that has been receiving a lot more attention with the growing concern for the environment. (6.5, 6.6) K/U
    (a) What are the economic advantages and disadvantages of using geothermal systems?
    (b) What are the environmental impacts of this technology when compared to the traditional use of fossil fuels?
    (c) Are there any limitations to how this technology could be used? Compare the suitability for using geothermal energy in Canada to that of other regions of North America.

Reflect on Your Learning

84. In this chapter, you learned what gives objects thermal energy and different ways in which this thermal energy can be transferred. C
    (a) How has your understanding of energy transfer changed from this knowledge? Do you feel that you have a better understanding of the thermal processes that take place in daily life?
    (b) Was there anything that you learned in this chapter that you found surprising? Was there anything specific that you learned that helped to clarify a concept of thermal energy?
85. Do you have a better understanding of the heating and cooling systems that are used in your household and most of the buildings in Canada? Do you have any more interest in this topic and field of work now that you have a better understanding? C

Research

GO TO NELSON SCIENCE

86. William Thomson, Lord Kelvin, set the value of absolute zero at 0 K, or –273 °C. Conduct research to determine whether this temperature has ever been recorded for any substance. Discuss the unusual properties of matter at or near absolute zero. Include details of at least one specific substance that exhibits odd behaviour when it cools down to close to absolute zero. T/I C A
87. Thermal energy from beneath Earth's surface was used in the past by the Romans, the Japanese, the Paleo-Indians of North America, and the Maoris of New Zealand for everyday uses. Choose one of these cultures and research how its people utilized geothermal energy. Include details, if applicable, of any systems that were used to transfer heat. T/I C A
88. Geothermal energy was not the only renewable form of energy that was used in cultures of the past. Other systems included utilization of wind and water for power and passive solar heating and cooling. Research one or more of these additional renewable energy designs that people used in ancient history. Include drawings or detailed descriptions of any of the energy systems, and describe the region(s) and cultures in which the system(s) were used. T/I C
89. Some towns and cities in Europe now run on 100 % renewable energy. Research these "green" cities, and devise a plan to convert your own town or city (or choose another town or city you know well) completely to renewable energy sources. Create a plan for your town or city, including the types of alternative energy you will use and the areas in which each type will be used, depending on location, climate, natural phenomena (such as wind or proximity to areas of high wind), geography, landscape, and existing energy systems. Create a timeline for conversion to alternative energy systems, and describe short- and long-term costs and savings, including predictions of whether the town or city will eventually be able to transfer energy back into the grid and actually make money. Describe positive and negative effects on the environment and the economy that may take place as a result of the conversion. T/I C
90. As in the case of James Joule, scientists throughout history have proposed new ideas based on investigations that went counter to the accepted theories of the day. These ideas were often met with skepticism and doubt, and sometimes even prosecution. Research one scientist whose findings were considered controversial at the time. Compare and contrast the scientist's theory with the general scientific beliefs on the topic during that time period. T/I C

CHAPTER

7

Nuclear Energy and Society

KEY CONCEPTS

After completing this chapter you will be able to

- distinguish between radioactive and stable materials
- explain what an isotope is and identify its physical characteristics
- describe and solve problems related to radioactive decay
- explain what is meant by and solve problems related to half-life
- describe and explain the concept of mass–energy equivalence
- calculate energy output of nuclear reactions
- describe and compare nuclear fission and nuclear fusion
- explain the fundamental principles of fission and fusion reactors
- analyze and discuss social and environmental issues related to the applications of nuclear energy

Where Does Nuclear Energy Come From, and What Are Its Applications?

For centuries, scientists believed that the atom was the fundamental building block of all matter. This changed when the nucleus of an atom was split for the first time in the early twentieth century. Nuclear physics was born! Scientists discovered that when an atom is split apart, a large amount of energy is released. This discovery led to the development of a number of applications, some of which you may be aware of, and some that will be new to you.

Mention the term “nuclear energy,” and people may think of large nuclear power reactors or perhaps nuclear weapons. The field of nuclear physics is much broader than that. Did you know, for example, that archaeologists use nuclear technology to estimate the age of fossils? Astrophysicists use similar techniques to estimate the age of moon rocks. Biologists are exploring nuclear methods to control harmful insect infestations.

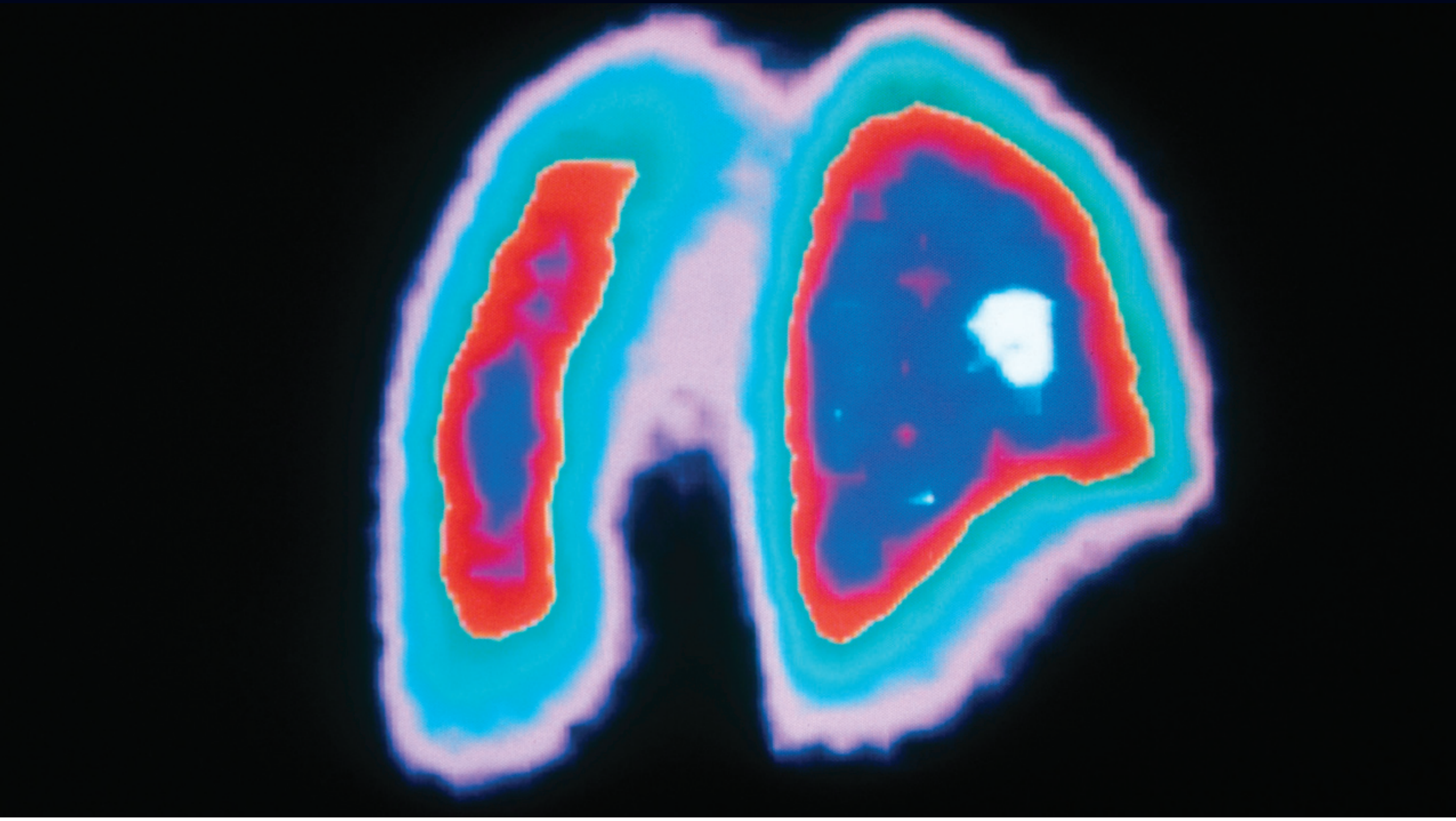
Nuclear medicine is one of the fastest growing fields of research involving nuclear energy. Materials with particular nuclear properties are useful for diagnosing, and sometimes treating, certain illnesses. Technetium-99m is an artificially created material used in organ scans. These scans provide vital information to medical experts that enables them to pinpoint malignant areas of a damaged organ and plan a suitable treatment.

In this chapter, you will learn about many important scientific discoveries related to nuclear energy and some of its applications. You will examine some of the issues related to the benefits and hazards of nuclear energy. As a student of science, it is your responsibility to critically examine all of the evidence available before constructing your own informed opinion on the relative merits of nuclear energy.

STARTING **POINTS**

Answer the following questions using your current knowledge. You will have a chance to revisit these questions later, applying concepts and skills from the chapter.

1. What types of particles make up atoms?
2. List what you know about each of these particles.
3. What applications of nuclear energy are you aware of?
4. Do you think that nuclear energy applications affect the environment? Explain why you think so.
5. What do you think “radioactive” means? Can you identify an example of a radioactive material?



Mini Investigation

Simulating Nuclear Reactions

Skills: Predicting, Performing, Observing, Analyzing, Evaluating

SKILLS HANDBOOK **A2.1, A6.5**

In a nuclear reaction, one substance spontaneously changes into another. In this investigation, you will use pennies (or two-colour tiles) to simulate a nuclear reaction and analyze the speed with which the reaction occurs.

Equipment and Materials: 100 pennies (or 100 two-colour tiles); paper bag; graph paper

1. Place the pennies in the bag. Let heads represent the atoms of the original substance and tails the atoms of the new substance. Predict the number of pennies that will come up heads when you pour the pennies out.
2. Trial 1: shake the bag and pour the pennies onto your lab bench. Count the number of heads and record your results in a table. Reflect on your prediction. Account for any discrepancies.
3. Put only the pennies that came up heads back into the bag. These represent the atoms that have not yet changed.
4. Suppose you repeated Steps 2 and 3 for several trials. Sketch a graph showing how you think the number of heads will decline over the next several trials. Give reasons for the shape of your graph.
5. Trial 2: pour the pennies again and tally the number of heads. Remove the pennies that come up tails and repeat for several trials until no pennies remain.
6. Create a scatter plot of number of pennies remaining versus trial number. Draw a smooth curve of best fit through the data.

A. Describe the shape of the curve. Does it have the same shape as your prediction? Explain why it has the shape it does. T/I C

B. How many trials did it take for all of the pennies to be removed? Compare this to the results of your classmates. Account for any discrepancies. T/I C

7.1 Atoms and Isotopes

The history of atomic discovery begins with the ancient Greeks, when, around 400 BCE, philosopher Democritus asserted that all material things are composed of extremely small irreducible particles called atoms. His theory was rejected and ignored for almost 2000 years. John Dalton resurrected the atomic theory of matter in the early nineteenth century by characterizing elements by their atomic structure and weight. Over the next hundred years or so, scientists continued to refine their understanding of the atom, until the advances of Niels Bohr and Ernest Rutherford.

Bohr–Rutherford Model of the Atom

Niels Bohr, a Danish scientist, and Ernest Rutherford, a New Zealand scientist, are credited with a number of discoveries that led to the development of the Bohr–Rutherford atomic model. Rutherford found that when a beam of positively charged particles was fired at a thin gold foil, most particles passed through the foil, as expected, but some were scattered in all directions. To explain this, it was proposed that the atom consists of a dense, positively charged nucleus surrounded by tiny negatively charged electrons and a relatively vast region of empty space. Bohr also discovered that the electrons could only occupy certain energy levels. When these discoveries were combined, the Bohr–Rutherford model of the atom was created.

This model has the following key features:

- The dense nucleus contains the atom's protons and neutrons.
- The relatively tiny electrons orbit the nucleus.
- The electrons only occupy certain energy levels.
- Most of the atom consists of empty space.

The model provides a visual method for describing the atomic structure of an element. The atomic structure refers to the number of protons, neutrons, and electrons in an atom and their organization within the atom. Simplified Bohr–Rutherford diagrams for helium and fluorine are shown in **Figure 1**.

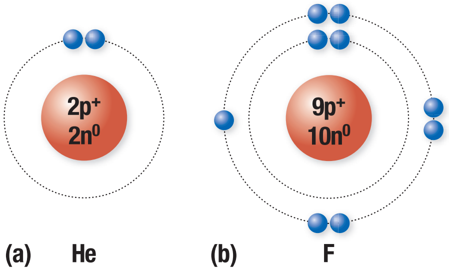


Figure 1 Bohr–Rutherford diagrams for (a) helium and (b) fluorine. Notice that a helium atom has two protons, two neutrons, and two electrons. A fluorine atom has nine protons, ten neutrons, and nine electrons.

proton a positively charged particle in the nucleus of an atom

neutron an uncharged particle in the nucleus of an atom

nucleons particles in the nucleus of an atom; protons and neutrons

electron a negatively charged particle found in the space surrounding the nucleus of an atom

ground state state in which all electrons are at their lowest possible energy levels

excited state state in which one or more electrons are at higher energy levels than in the ground state

The nucleus is the centre of the atom and consists of protons and neutrons. A **proton** is a positively charged particle, and a **neutron** is an uncharged particle. In nuclear physics, neutrons and protons are often referred to collectively as **nucleons**. Protons and neutrons have approximately the same mass. An **electron** is a negatively charged particle that moves in the space surrounding the nucleus and is extremely small compared to nucleons. In general, an atom in its normal state has the same number of electrons as protons.

In a Bohr–Rutherford diagram, electrons are placed in the lower energy levels, or shells, first, until these shells are filled. Atoms that have electrons placed in this way are said to be in their **ground state**: the electrons are all at the lowest possible energy levels. An atom is said to be in an **excited state** if it absorbs energy that causes an electron to have more energy and move to a higher energy level. An excited atom returns to its ground state by releasing energy as the electron drops back to its lowest available energy level. **Figure 2** shows a hydrogen atom in the ground state and in an excited state. The first energy level is the innermost shell in the Bohr–Rutherford diagram.

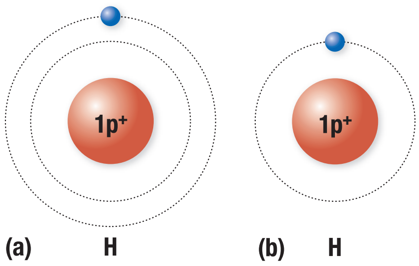


Figure 2 Hydrogen in (a) an excited state and (b) its ground state

According to the Bohr–Rutherford model, each energy level or shell can hold a certain number of electrons. **Table 1** gives the maximum number of electrons for each shell.

Table 1 Electron Distribution in a Bohr–Rutherford Model

Shell number	Maximum number of electrons
1	2
2	8
3	18
4	32

Atomic Number, Mass Number, and the Periodic Table

The periodic table of elements lists all the elements known today. It can be used to determine the atomic structure of an element (**Figure 3**).

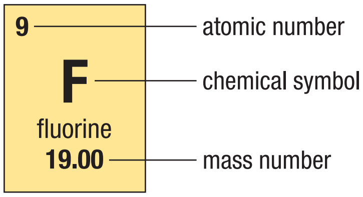


Figure 3 Identifying mass number and atomic number for the element fluorine on the periodic table

The **atomic number** is the number of protons in an atom of an element. Each element has a different number of protons. The **mass number** is equal to the number of nucleons in an atom. The periodic table entry shown in Figure 3 indicates that fluorine has nine protons and nine electrons. The number of neutrons is determined by subtracting the atomic number from the mass number:

19 nucleons (mass number) − 9 protons (atomic number) = 10 neutrons

atomic number the number of protons in the nucleus

mass number the number of protons and neutrons in the nucleus

Isotopes

Carbon-12 consists of six protons and six neutrons (**Figure 4**). Most naturally occurring carbon has this atomic structure. There is, however, another form of carbon called carbon-14. Carbon-14 has six protons and eight neutrons. Carbon-14 is a different **isotope** than carbon-12. Different isotopes of an element have the same number of protons, but different numbers of neutrons (**Figure 5**). The mass number of 14 indicates that an atom of carbon-14 has two more neutrons than an atom of carbon-12.

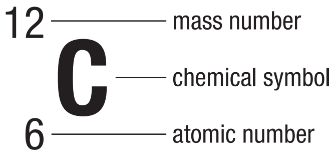


Figure 4 The standard notation for carbon-12

isotope a form of an element that has the same atomic number, but a different mass number than all other forms of that element

number of neutrons = mass number − atomic number

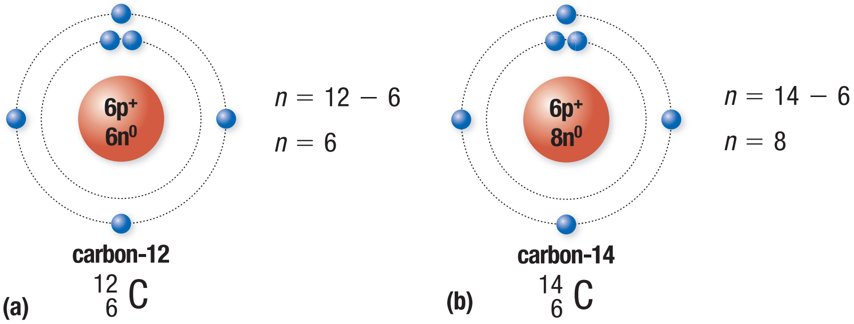


Figure 5 Bohr–Rutherford models for (a) carbon-12 and (b) carbon-14

Carbon-14 has some interesting properties that are useful to archaeologists and scientists. A process called carbon dating provides a reasonably accurate method to determine the age of fossils and objects made of things that were once alive. You will learn more about carbon dating in Section 7.3.

Most samples of elements consist of a number of different isotopes, some occurring naturally and others produced in laboratories. The most common isotope of hydrogen has a nucleus consisting of only one proton. There are, however, two other isotopes of hydrogen. These isotopes are important in nuclear science, so they have been given their own names: deuterium and tritium. Deuterium, which has one proton and one neutron, is a naturally occurring substance. Tritium, which has one proton and two neutrons, is only produced as a by-product of human-made nuclear reactions.

The periodic table identifies the most commonly occurring isotopes for each element. A more general table that lists atomic information for all known isotopes is called a chart of the nuclides. In the following Tutorial, you will draw Bohr–Rutherford diagrams for various isotopes.

LEARNING **TIP**

Mass Numbers

The mass numbers of most elements have decimal values associated with them. Carbon-12 has a mass of exactly 12 atomic units because it is the substance to which all other elements are compared by atomic mass. The mass number that appears in the periodic table for carbon is slightly higher than 12 because of the small amounts of carbon-14 that exist in nature.

Tutorial 1 Constructing a Bohr–Rutherford Diagram

Sample Problem 1

Draw the Bohr–Rutherford diagram for silicon-31.

Step 1. Locate silicon on the periodic table. The chemical symbol for silicon is Si.

Step 2. The mass of this isotope is given: 31. Use a periodic table to identify the atomic number. The atomic number is 14.

Step 3. Since the atomic number is 14, there are 14 protons and 14 electrons. The number of neutrons is found by subtracting the atomic number from the mass number: $31 - 14 = 17$

There are 17 neutrons in an atom of silicon.
Use this information to draw a Bohr–Rutherford diagram for silicon (**Figure 6**).

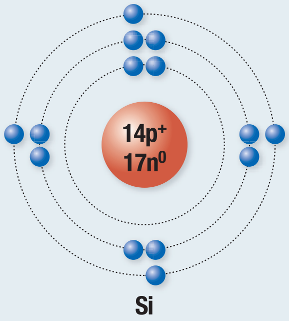


Figure 6

Practice

1. Sketch a Bohr–Rutherford diagram for each element. T/I C
   (a) aluminum, Al (mass number 28)
   (b) silver, Ag (mass number 110)
   (c) two other elements of your choice from the periodic table or Appendix B (page 662)

radioisotope an unstable isotope that spontaneously changes its nuclear structure and releases energy in the form of radiation

radiation energy released when the nucleus of an unstable isotope undergoes a change in structure

Some isotopes, called **radioisotopes**, are unstable; that is, they spontaneously change their nuclear structure. **Radiation** is energy released in the form of waves when a radioisotope undergoes a structural change. This radiation can be harmful if not properly controlled. In some cases, however, these radioisotopes are beneficial. You will examine the process by which isotopes spontaneously change later in this chapter.

Medical Applications of Radioisotopes

Nuclear medical imaging is a diagnostic technique that involves injecting a patient with a small dose of a radioisotope, such as technetium-99m. These materials, sometimes called radioactive tracers, emit radiation that can be detected and converted into an image. By comparing radiation patterns of an unhealthy organ to those of a healthy one, doctors are better able to pinpoint a malignancy, or tumour (**Figure 7**). One of the advantages of nuclear imaging over traditional X-rays is that it provides a detailed account of both hard tissues like bone and softer tissues like the liver and kidneys. X-rays are primarily useful for detecting bone fractures.

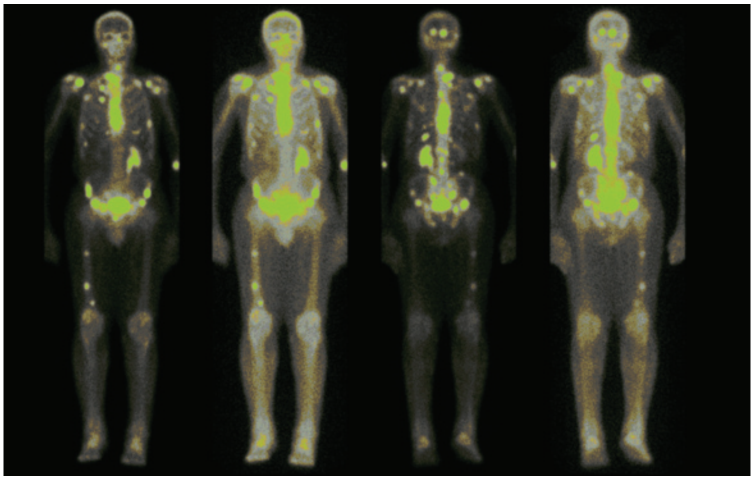


Figure 7 A radioactive tracer provides a detailed image of a diseased organ. This image is detecting the spread of lung cancer to the skeleton.

Research This

Technetium-99m

Skills: Researching, Analyzing, Communicating

SKILLS HANDBOOK A5.1

Technetium-99m is an unusual isotope for which medical scientists have discovered several important uses. The “m” in its name identifies it as a meta-stable isotope.

1. Research Technetium-99m (Tc-99m) on the Internet or at the library. Write a brief report of your findings that includes answers to the following questions:

A. What is a meta-stable isotope? T/I

B. How is Tc-99m obtained? T/I

C. What is it about Tc-99m that makes it particularly useful in medicine? T/I

D. Discuss some of the applications of Tc-99m in the medical field. A

E. Are there any drawbacks to using nuclear imaging, such as health risks, costs, or wait times? A

GO TO NELSON SCIENCE

Medical Treatments

One of the earliest medical applications of radioisotopes began in the 1950s, when iodine-131 was used to diagnose and treat thyroid disease. Sufferers of hyperthyroidism have an overactive thyroid gland: it releases more thyroid hormone than the body requires. Iodine-131 can be used to both identify a diseased thyroid gland and halt production of the hormone.

Radionuclide therapy (RNT) is a rapidly growing medical field in which the properties of certain radioactive substances are used to treat various ailments. RNT is currently used to treat certain types of tumours, bone pain, and other conditions. In cancer treatments, the fundamental idea behind RNT is to bombard rapidly dividing harmful cells with radiation. These cells tend to absorb the radiation, which prevents them from dividing further.

CAREER LINK

A radiation therapist works with doctors, other medical staff, and patients to design and administer radiation health treatment plans. To learn more about careers in radiation therapy and related fields,

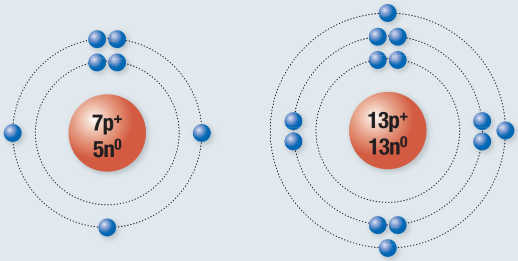
GO TO NELSON SCIENCE

7.1 Summary

- The Bohr–Rutherford model of the atom illustrates the atomic structure of an element.
- You can identify the number of protons, neutrons, and electrons of an element from its Bohr–Rutherford model.
- You can identify the mass number and atomic number of an element from the periodic table.
- Isotopes of an element have the same number of protons but different numbers of neutrons.
- Radioactive isotopes are unstable and will spontaneously undergo a change in their nuclear structure.
- Some radioactive isotopes have useful applications, such as medical diagnosis and therapy.

7.1 Questions

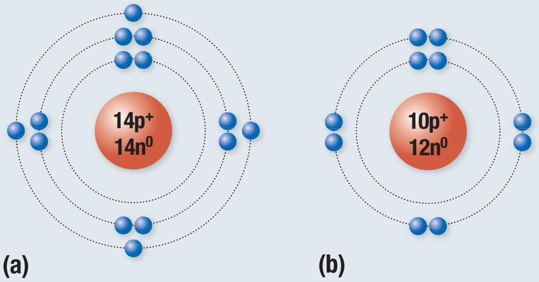
1. Draw a Bohr–Rutherford diagram for each isotope. K/U C
   (a) oxygen-16
   (b) potassium-40
2. (a) Draw Bohr–Rutherford diagrams for hydrogen, deuterium, and tritium.
   (b) Identify their similarities and differences. K/U C
3. For each Bohr–Rutherford model shown in **Figure 8**,
   (a) determine the atomic number and the mass number
   (b) write the chemical name of the isotope K/U



(i) **(ii)**

Figure 8

4. (a) Draw a Bohr–Rutherford diagram for each isotope of beryllium.
   (i) $^{7}_{4}$Be
   (ii) $^{9}_{4}$Be
   (iii) $^{11}_{4}$Be
   (b) Explain the similarities and differences between these models.
   (c) Which isotope of beryllium is the most common in nature? Explain how you know. K/U C
5. (a) Draw a Bohr–Rutherford model for each isotope.
   (i) lithium-5, $^{5}_{3}$Li
   (ii) oxygen-20, $^{20}_{8}$O
   (b) Describe how each isotope compares with its most commonly occurring isotope. K/U C
6. Identify each isotope shown in **Figure 9** given its Bohr–Rutherford diagram. K/U



(a) **(b)**

Figure 9

7. An isotope has 16 protons and 22 neutrons. Identify the element. K/U
8. (a) Draw a Bohr–Rutherford model for each isotope of argon.
   (i) Ar-40 (ii) Ar-44 (iii) Ar-47
   (b) Explain how these isotopes are
   (i) alike
   (ii) different K/U C
9. Neon has three stable isotopes: Ne-20, Ne-21, and Ne-22. K/U C
   (a) Draw a Bohr–Rutherford model for each isotope.
   (b) How are these models alike? How are they different?
10. (a) Draw Bohr–Rutherford models for lithium-10, beryllium-10, and boron-10.
   (b) How are these models alike? How are they different? K/U C

Radioactive Decay

7.2

A fascinating area of scientific inquiry around the turn of the twentieth century was the splitting of the atom. In 1896, Henri Becquerel observed this as a naturally occurring event when he found that a sample of uranium left an image when placed on photographic film. This eventually led to the discovery of **radioactivity**—the spontaneous disintegration of an atom's nucleus. The film traces were caused by particles emitted during this process.

radioactivity a process by which the nucleus of an atom spontaneously disintegrates

Becquerel's accidental discovery encouraged scientists to seek ways to induce similar reactions using various materials. Ernest Rutherford used high-energy particles to bombard nitrogen and discovered that oxygen was produced. A few years later, James Chadwick performed a similar experiment with beryllium that led to the discovery of the neutron. These efforts helped scientists develop a better understanding of atomic structure at the nuclear level and formed the basis for the broad range of nuclear scientific work that followed. As you learned in Chapter 5, a reaction in which the nucleus of an atom is split into smaller pieces is known as **nuclear fission**.

nuclear fission the decomposition of large, unstable nuclei into smaller, more stable nuclei

A cyclotron, shown in **Figure 1**, is a device that can accelerate particles to very high speeds. Many nuclear reactions can only occur when particles are travelling at speeds near to that of light. High-energy physics is the study of such interactions.

Figure 1 A cyclotron is a device that accelerates particles to very high speeds approaching the speed of light. The high-energy particles that are produced can be used for research experiments, as well as medical treatments.

Chemical Reactions

A chemical reaction is the interaction of substances to form new substances. The initial substances, which may be elements or compounds, are called reactants. The substances present at the end of the reaction, which also may be elements or compounds, are called products. For example, the reaction between carbon and oxygen produces carbon dioxide. The reactants are carbon, C, and oxygen, O_2. The product is carbon dioxide, CO_2. Energy is also released during this chemical reaction.

We can represent a chemical reaction as a word equation or a chemical equation as follows:

word equation: carbon + oxygen → carbon dioxide + energy

chemical equation: $C + O_2 \rightarrow CO_2 + \text{energy}$

In a chemical reaction, the entities do not change. All of the entities that were present in the reactants are present in the products. A balanced chemical reaction clearly shows this. In the previous example, there is one atom of carbon on each side of the arrow. Similarly, there are two atoms of oxygen on either side of the arrow. The identities of the elements do not change; only their organization changes. Chemical reactions obey the law of conservation of mass.

A chemical reaction, such as the previous example, that releases energy is exothermic. By contrast, a chemical reaction that absorbs energy is endothermic.

Nuclear Reactions

nuclear reaction the process by which the nucleus of an atom sometimes changes

Nuclear reactions involve changes in the nuclei of atoms, sometimes resulting in completely new elements. The identity of an element is determined by examining the number of protons in its nucleus. If the number of protons changes, one or more new elements result. By examining the forces present in a nucleus, it is possible to understand the nature of nuclear reactions and why they occur.

Electrostatic Force and the Strong Nuclear Force

electrostatic force the force of attraction or repulsion due to electric charges

For over a hundred years, scientists have understood the **electrostatic force** of attraction and repulsion between electrically charged particles. Like charges repel, and opposite charges attract. This explains why the positively charged nucleus of an atom attracts negatively charged electrons. It cannot, however, explain how the nucleus itself is held together. Consider the helium nucleus shown in **Figure 2**. The neutrons have no electrical charge and the protons are both positively charged. What is holding the nucleus together?

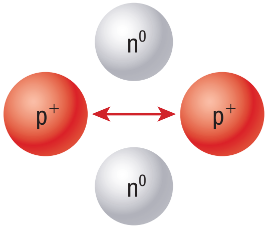


Figure 2 The nucleons in a helium nucleus

strong nuclear force the very strong force of attraction between nucleons

A different type of force, not discovered until the 1930s, is responsible for holding the nucleus together. Like gravity, and unlike the electrostatic force, the **strong nuclear force** is always attractive and helps hold together the neutrons and protons in the nucleus of an atom. The strong nuclear force is much stronger than the electrostatic force. The strong nuclear force is responsible only for holding the nucleus of an atom together.

Stable and Unstable Isotopes

There is a delicate balance between the repulsive electrostatic force and the attractive strong nuclear force in a nucleus. When these forces are balanced, an atom is said to be stable. Atoms with higher atomic numbers (more protons) experience a greater electrostatic force of repulsion among the protons, and the protons become more separated. This separation results in a weakening of the strong nuclear force. Additional neutrons add to the strong nuclear force to balance the increasing electrostatic repulsion.

radioactive decay the process by which a radioactive atom's nucleus breaks apart and forms different atoms

Sometimes the electrostatic forces are great enough to overcome the strong nuclear force, and the nucleus spontaneously disintegrates (breaks apart) and releases energy. An unstable atom with a nucleus that can spontaneously disintegrate is said to be radioactive. The process by which a radioactive atom spontaneously breaks apart to form smaller atoms is called **radioactive decay**. There are three common forms of radioactive decay: alpha decay, beta decay, and gamma decay.

Alpha Decay

One of the most common forms of radioactive decay is **alpha decay**, or α-decay. In alpha decay, a helium nucleus, consisting of two protons and two neutrons, is spontaneously emitted from the nucleus. An illustration of alpha decay is shown in **Figure 3.**

alpha (α) decay nuclear reaction in which an alpha particle is emitted

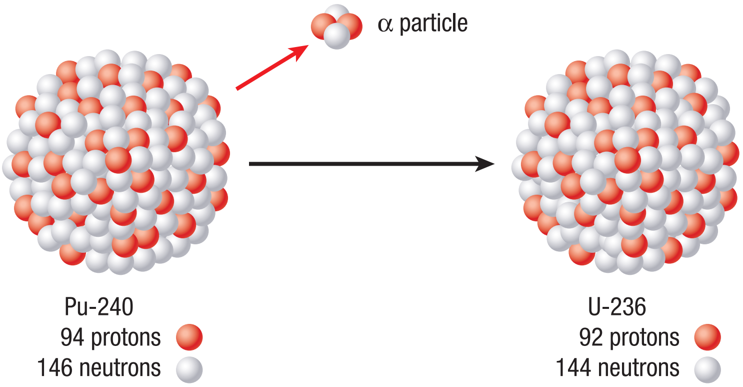


Figure 3 Alpha decay of plutonium-240

In **Figure 3**, an atom of plutonium-240 decays into uranium-236, and a helium-4 nucleus is emitted in the process. The helium-4 nucleus is called an **alpha particle**. The equation for this nuclear reaction is

$${}^{240}_{94}\text{Pu} \rightarrow {}^{236}_{92}\text{U} + {}^{4}_{2}\text{He}$$

alpha particle a particle emitted during alpha decay; composed of a helium nucleus containing two protons and two neutrons

When a substance undergoes alpha decay, the mass number (A) is reduced by four and the atomic number (Z) is reduced by two. Generally, this can be shown as

$${}^{A}_{Z}\text{X} \rightarrow {}^{A-4}_{Z-2}\text{Y} + {}^{4}_{2}\text{He}$$

In a nuclear reaction, the **parent atom** (X) is the reactant atom, and the **daughter atom** (Y) is the product atom. The atomic number changes during alpha decay, so a new atom (element) is formed. When this happens, the nuclear reaction is said to be a **transmutation**.

In the following Tutorial, you will use your understanding of alpha decay to write the equation for a nuclear reaction.

parent atom the reactant atom in a nuclear reaction

daughter atom the product atom in a nuclear reaction

transmutation a nuclear decay process in which daughter atoms are different elements from parent atoms

Tutorial 1 Determining the Nuclear Equation for Alpha Decay

Sample Problem 1

When lead-204 undergoes alpha decay, it produces a stable isotope. Determine the element and its atomic number and mass number. Write the nuclear reaction equation for this alpha decay.

Step 1. Use the periodic table to determine that the atomic number of lead is 82.

Step 2. Determine the atomic number and mass number of the new isotope using the equation for alpha decay.

$${}^{204}_{82}\text{Pb} \rightarrow {}^{204-4}_{82-2}\text{Y} + {}^{4}_{2}\text{He}$$

We can see that the new element has the atomic number 80 and mass number 200.

$${}^{204}_{82}\text{Pb} \rightarrow {}^{200}_{80}\text{Y} + {}^{4}_{2}\text{He}$$

The periodic table tells us that the new element is an isotope of mercury.

The daughter atom is mercury-200.

Step 3. Write the reaction equation:

$${}^{204}_{82}\text{Pb} \rightarrow {}^{200}_{80}\text{Hg} + {}^{4}_{2}\text{He}$$

Practice

1. Determine the element that is produced when plutonium-239 undergoes alpha decay, and write the reaction equation. T/I C [ans: uranium-235; ${}^{239}_{94}\text{Pu} \rightarrow {}^{235}_{92}\text{U} + {}^{4}_{2}\text{He}$]
2. When an unknown isotope undergoes alpha decay, neptunium-239 is produced. Determine the unknown isotope. T/I [ans: americium-243]

beta (β) decay nuclear reaction in which a beta particle is emitted or captured

beta particle a high-energy electron or positron ejected or captured by a nucleus during beta decay

positron a particle with a positive charge and the same mass as an electron

Beta Decay

Beta decay, or β-decay, is a type of nuclear decay reaction that involves the emission or capture of a beta particle. A **beta particle** is either an electron or a positron. A **positron** is a particle similar to an electron except that it has a positive charge instead of a negative charge. There are three main types of beta decay: beta-negative (β^-) decay, beta-positive (β^+) decay, and electron capture.

BETA-NEGATIVE DECAY

In a beta-negative decay reaction, an electron is emitted from the nucleus of a parent atom. How can this happen, since electrons are not usually found in the nucleus of an atom? When a nucleus contains too many neutrons, the strong nuclear force becomes much greater than the electrostatic force. To maintain stability, a neutron spontaneously decays into a proton and an electron, and the electron is ejected from the nucleus. An example of a beta-negative decay reaction is the decay of tritium (hydrogen-3) to helium-3, as shown in **Figure 4**.

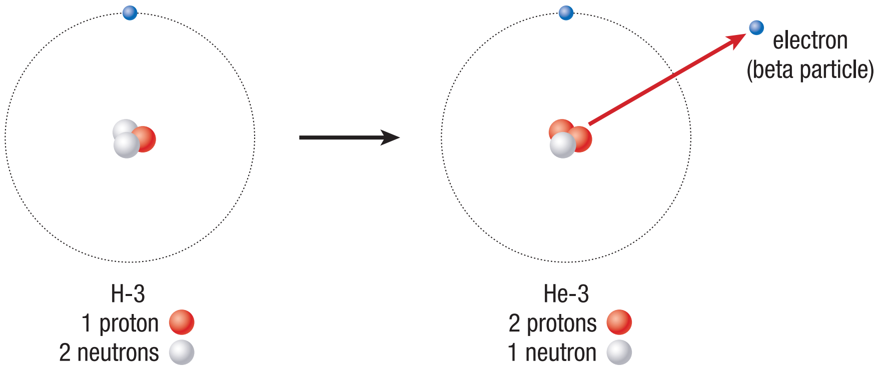


Figure 4 Beta-negative decay of tritium (H-3)

The equation for this reaction is

$${}^{3}_{1}\text{H} \rightarrow {}^{3}_{2}\text{He} + {}^{0}_{-1}\text{e}$$

where ${}^{0}_{-1}\text{e}$ represents an electron (the negative beta particle). In this process, the mass number of the daughter nucleus remains unchanged, but the atomic number increases by one. This process is a transmutation because the number of protons changes. The general equation for beta-negative decay is

$${}^{A}_{Z}\text{X} \rightarrow {}^{A}_{Z+1}\text{Y} + {}^{0}_{-1}\text{e}$$

BETA-POSITIVE DECAY

In beta-positive decay, a proton changes into a neutron and a positron, which is symbolized by ${}^{0}_{+1}\text{e}$. An example of this type of nuclear reaction is the decay of carbon-11 into boron-11, as shown in **Figure 5**.

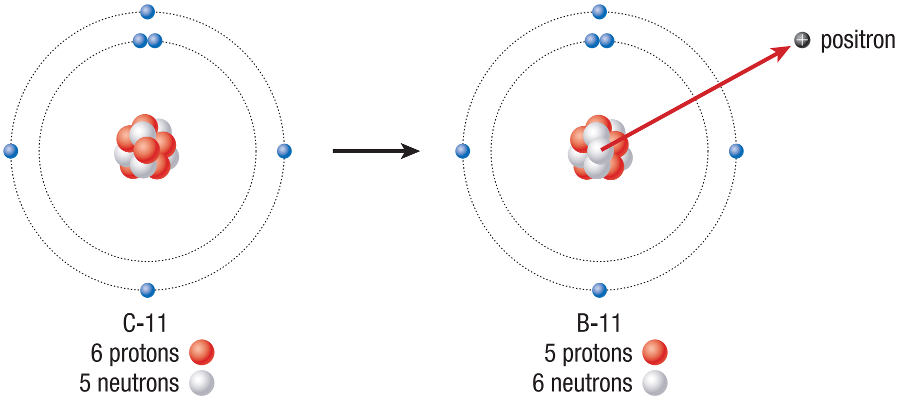


Figure 5 Beta-positive decay of carbon-11

The equation for this nuclear reaction is

$${}^{11}_{6}\text{C} \rightarrow {}^{11}_{5}\text{B} + {}^{0}_{+1}\text{e}$$

Notice that in this process, the mass number of the daughter nucleus remains unchanged, but the atomic number decreases by one. This process is a transmutation because a different type of element is formed when a proton in the nucleus of the parent atom changes into a neutron. The general equation for beta-positive decay is

$${}^{A}_{Z}\text{X} \rightarrow {}^{A}_{Z-1}\text{Y} + {}^{0}_{+1}\text{e}$$

ELECTRON CAPTURE

Electron capture is a form of beta decay in which an electron is absorbed by a nucleus and combines with a proton to form a neutron, as shown in **Figure 6**.

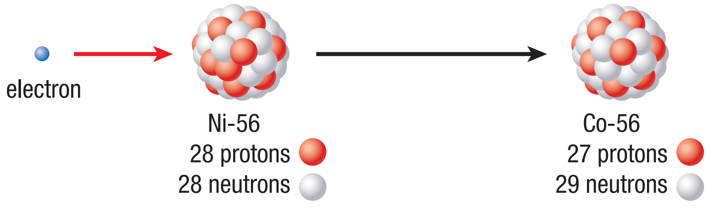


Figure 6 Electron capture

The equation for this reaction is

$${}^{56}_{28}\text{Ni} + {}^{0}_{-1}\text{e} \rightarrow {}^{56}_{27}\text{Co}$$

In this process, the mass number of the daughter nucleus remains unchanged, but the atomic number decreases by one. This process is a transmutation because the number of protons changes. The general equation for electron capture decay is

$${}^{A}_{Z}\text{X} + {}^{0}_{-1}\text{e} \rightarrow {}^{A}_{Z-1}\text{Y}$$

In the following Tutorial, you will use what you have learned about beta decay to determine an unknown isotope and a nuclear equation for a reaction.

Tutorial 2 Determining the Nuclear Equation for Beta Decay

In this Sample Problem, you will determine the daughter element produced by the beta-negative decay of a known element.

Sample Problem 1

When bismuth-214 undergoes beta-negative decay, it produces a stable isotope. Determine the element and its atomic number and mass number. Write the nuclear reaction equation for this beta decay.

Step 1. Use a periodic table to determine that the atomic number of bismuth is 83.

Step 2. Determine the atomic number and mass number of the new isotope using the equation for beta-negative decay.

$${}^{214}_{83}\text{Bi} \rightarrow {}^{214}_{83+1}\text{Y} + {}^{0}_{-1}\text{e}$$

We can see that the new element has the atomic number 84 and mass number 214.

$${}^{214}_{83}\text{Bi} \rightarrow {}^{214}_{84}\text{Y} + {}^{0}_{-1}\text{e}$$

The periodic table tells us that the new element is polonium-214.

Step 3. Write the reaction equation.

$${}^{214}_{83}\text{Bi} \rightarrow {}^{214}_{84}\text{Po} + {}^{0}_{-1}\text{e}$$

Practice

1. Determine the element that is produced when cerium-141 undergoes beta-negative decay and write the reaction equation. T/I C [ans: praseodymium-141; ${}^{141}_{58}\text{Ce} \rightarrow {}^{141}_{59}\text{Pr} + {}^{0}_{-1}\text{e}$]
2. Determine the element that is produced when chromium-46 undergoes beta-positive decay. Then write the reaction equation. T/I C [ans: vanadium-46; ${}^{46}_{24}\text{Cr} \rightarrow {}^{46}_{23}\text{V} + {}^{0}_{+1}\text{e}$]

Gamma Decay

After a nuclear reaction such as alpha or beta decay has occurred, the daughter nucleus is in a high-energy, or excited, state. As a result, the nucleus spontaneously releases energy in the form of a gamma ray in order to return to a lower, more stable energy state. A gamma ray is a highly energetic form of electromagnetic radiation that is emitted as a photon. A **photon** is a particle with zero mass and a high level of energy. This process is called **gamma decay**, or γ-decay. For example, the helium-3 daughter resulting from the beta decay reaction in Figure 4 will undergo gamma decay, as shown in **Figure 7**. The general equation for gamma decay is

photon a high-energy particle with no mass

gamma (γ) decay a reaction in which an excited nucleus returns to a lower, more stable energy state, releasing a very high-energy gamma ray in the process

$$^{3}_{2}\text{He}^{*} \rightarrow {}^{3}_{2}\text{He} + {}^{0}_{0}\gamma$$

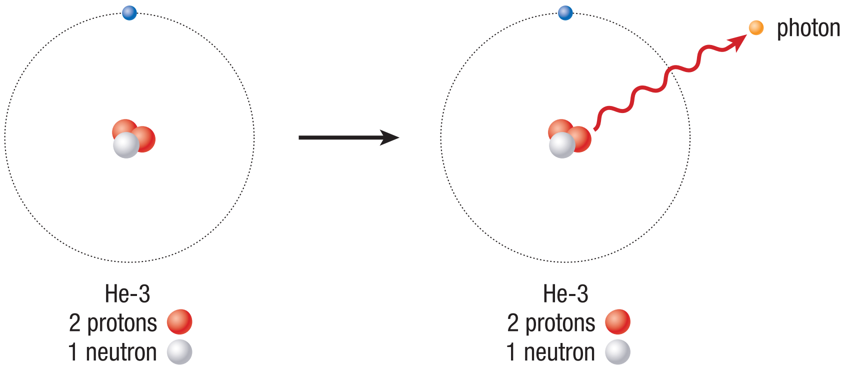


Figure 7 Gamma decay of helium-3

The symbol for a photon is $^{0}_{0}\gamma$. Notice that the parent and daughter nuclei are identical. Only the energy level of the nucleus has changed. The asterisk is used to indicate that the parent in this reaction is in an excited state. Notice that the mass number and atomic number of a gamma ray are both zero. In the following Tutorial, you will determine the nuclear equation for a gamma decay reaction.

Tutorial 3 Determining the Nuclear Equation for Gamma Decay

In this Sample Problem, you are given the parent element and must determine the gamma decay equation for this reaction.

Sample Problem 1

When dysprosium-152 undergoes gamma decay, its nucleus changes from an excited state to a stable state. Write the nuclear reaction equation for this gamma decay.

Step 1. Use a periodic table to determine that the atomic number of dysprosium is 66.

Step 2. Determine the atomic number and mass number of the new isotope. In gamma decay, both the atomic number and the mass number remain unchanged.

Step 3. Write the reaction equation. In gamma decay a gamma ray is ejected from the nucleus. An asterisk is used to signify a nucleus in its excited state.

$$^{152}_{66}\text{Dy}^{*} \rightarrow {}^{152}_{66}\text{Dy} + {}^{0}_{0}\gamma$$

Practice

1. Write the reaction equation when plutonium-240 undergoes gamma decay. T/I C [ans: $^{240}_{94}\text{Pu}^{*} \rightarrow {}^{240}_{94}\text{Pu} + {}^{0}_{0}\gamma$].
2. Is gamma decay an example of a transmutation? Explain why or why not. K/U

Characteristics of Radioactive Decay

Alpha particles, beta particles, and gamma rays all pose a danger to living tissue because they can ionize, or strip the electrons from, atoms. Types of radiation that can ionize atoms are known as ionizing radiation. When ionizing radiation makes contact with living tissue, it can result in burns, tumours, and other harmful effects. It is important to protect tissues from exposure to ionizing radiation.

Alpha particles have a strong ionizing ability due to their positive charge and relatively high mass. Fortunately they travel a relatively short distance before becoming absorbed, so their potential danger is minimal unless they are ingested or inhaled. Beta particles and gamma rays, however, have a greater penetrating range in air and must be shielded against. **Table 1** summarizes the characteristics of the three types of ionizing radiation you learned about in this section.

Table 1 Characteristics of Radioactive Decay

Type of decay	Radiation	Emitted particle	Electric charge	Penetrating ability
alpha decay	alpha particle	helium nucleus ($^{4}_{2}\text{He}$)	$+2$	can penetrate skin or paper, but is slow moving
beta-negative decay	beta particle	electron ($^{0}_{-1}\text{e}$)	-1	can penetrate a few sheets of aluminum foil
beta-positive decay	beta particle	positron ($^{0}_{+1}\text{e}$)	$+1$	
electron capture	—	no particle is emitted	—	not applicable
gamma decay	gamma rays	photon ($^{0}_{0}\gamma$)	0	can penetrate a few centimetres of lead

7.2 Summary

- The strong nuclear force is responsible for holding the nucleus of an atom together by balancing the proton-proton electrostatic forces of repulsion.
- Nuclear reactions are reactions that involve the nucleus of an atom, where high-energy electromagnetic radiation is either emitted or absorbed.
- Radioactive decay is a process by which the nucleus of a radioisotope spontaneously changes.
- There are three common types of radioactive decay: alpha decay, beta decay, and gamma decay.
- Alpha particles, beta particles, and gamma rays are forms of ionizing radiation.

7.2 Questions

1. Write the nuclear reaction equation for each atom undergoing alpha decay (refer to the periodic table). K/U
   (a) curium-248
   (b) radium-223
2. Write the nuclear reaction equation for each atom undergoing beta-negative decay (refer to the periodic table). K/U
   (a) sulfur-35
   (b) gold-198
3. Write the nuclear reaction equation for each atom undergoing beta-positive decay (refer to the periodic table). K/U
   (a) sodium-22
   (b) calcium-39
4. The positron is a very interesting particle. Conduct some research on the positron and describe some of its properties. Summarize your findings in a one-page report. T/I C
5. Write nuclear reaction equations for each atom undergoing electron capture (refer to the periodic table). K/U
   (a) potassium-40
   (b) carbon-11
6. The strong nuclear force has a peculiar property. At distances less than 0.5 femtometres (5×10^{-16} m), the force reverses from strong attraction to strong repulsion. Suggest why this might be necessary. C A

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7.3

Half-Life

Radioactive decay reactions have applications in a wide range of fields. For example, in 1996 the remains of a prehistoric man, shown in **Figure 1**, were found in Kennewick, Washington. Scientists used the properties of radioactive decay to determine that the remains belonged to a man who lived over 9000 years ago! This discovery has led to further information about North American ancestry and the evolution of humans as a species. We will explore the techniques that were used to date this fascinating artifact in this section.

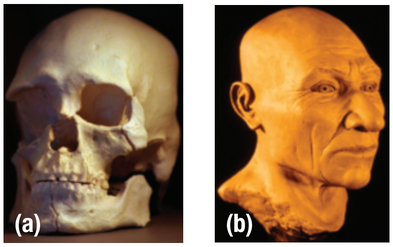

Figure 1 (a) Skull of Kennewick man (b) Reconstruction of Kennewick man

Measuring the Rate of Radioactive Decay Processes: Half-Life

half-life the average length of time it takes radioactive material to decay to half of its original mass

Radioactive decay reactions are spontaneous. There is no way to predict exactly when a particular unstable nucleus will disintegrate. However, it is possible to predict the decay rate for a large sample of an isotope. Radioactive materials decay at different rates, which can vary significantly. The average length of time it takes a radioactive material to decay to half its original mass is called the **half-life**.

The half-life of any given isotope is actually an average time for a particular parent atom to decay to its daughter atom. Cobalt-60, for example, has a half-life of 5.27 years. This does not mean that every atom of this isotope decays to its daughter atom after 5.27 years. Some atoms decay sooner, and some later. On average, however, it takes 5.27 years for an atom of cobalt-60 to decay. The larger the sample size, the more accurately a material decays according to its half-life.

Mini **Investigation**

Analyzing Half-Life

Skills: Predicting, Performing, Observing, Analyzing, Communicating

SKILLS HANDBOOK **A6.5**

When a radioactive material decays, the amount of the parent decreases, while the amount of the daughter increases. How can these relationships be represented graphically?

Equipment and Materials: periodic table; graph paper or graphing technology; half-life simulation applet (optional)

1. Carbon-15 with a half-life of 2.5 s decays to nitrogen-15. Suppose a sample of carbon-15 has an initial mass of 256 mg. Copy and complete **Table 1**. Assume that mass is conserved.

Table 1

Time (s)	Mass of C-15 (mg)	Mass of N-15 (mg)	Total mass (mg)
0	256	0	256
2.5	128	128	256
5			
7.5			

2. Predict the shape of the graph of mass of carbon-15 versus time. Explain your reasoning. Plot a graph of mass of carbon-15 versus time, with time on the horizontal axis. Use a smooth curve to join the points.
3. Repeat Step 2 for the graph of the mass of nitrogen-15 versus time. Plot both graphs on the same grid.

A. What type of radioactive decay is this reaction? Explain how you know. K/U C

B. Write the nuclear reaction equation. T/I C

C. Discuss the rates of change for carbon-15 and nitrogen-15. Explain why the two graphs have the shapes that they do. T/I C

D. Interpret the point of intersection of the two graphs. Explain what each coordinate of this point represents. T/I C

Mathematical Models Using Half-Life

Radioactive decay is an example of an exponential relationship—as time increases, the mass of a radioactive isotope remaining in a sample decreases at an exponential rate. The rate of decay is greater in the initial stages of the process because there are more atoms to decay. The rate of decay continuously decreases as the sample gets smaller and smaller. The mass, A, of a radioactive material with an initial sample mass of A_0 is related to time, t, and half-life, h. This can be represented by the following equation:

$$A = A_0\left(\frac{1}{2}\right)^{\frac{t}{h}}$$

When using this equation it is important to measure the masses A and A_0 using the same units. The same is true for t and h. In the following Tutorial, you will apply this equation to solve problems involving the half-life of radioactive isotopes.

LEARNING **TIP**

The Half-Life Equation

The exponent $\frac{t}{h}$ is time divided by half-life. This quotient represents the number of half-lives, which is the number of times the initial amount is reduced by one-half.

Tutorial **1** Calculations Involving Half-Life

Sample Problem 1

Neon-19 has a half-life of 17.22 s. What mass of neon-19 will remain from a 100 mg initial sample after 30 s?

Given: $A_0 = 100$ mg; $h = 17.22$ s; $t = 30$ s

Required: A

Analysis: $A = A_0\left(\frac{1}{2}\right)^{\frac{t}{h}}$

Solution: $A = A_0\left(\frac{1}{2}\right)^{\frac{t}{h}}$

$$= (100\text{ mg})\left(\frac{1}{2}\right)^{\frac{30\,\cancel{\text{s}}}{17.22\,\cancel{\text{s}}}}$$

$$= (100\text{ mg})\left(\frac{1}{2}\right)^{1.7422}$$

$$A = 30\text{ mg}$$

Statement: There will be 30 mg of neon-19 remaining after 30 s.

Sample Problem 2

A 100 mg sample of magnesium-27 decays by 7 % of its previous mass every minute. Determine its half-life and state the half-life decay equation.

Step 1. The decay of magnesium-27 can be modelled using a table or graph. If 7 % decays during each minute, then 93 % remains. Create a table similar to **Table 2** to determine the mass remaining after each minute.

Table 2 Mass of Magnesium-27 Remaining

Time (min)	Initial mass (mg)	Final mass (mg)
0	100	0.93(100) = 93
1	93	0.93(93) = 86.49
2	86.49	0.93(86.49) = 80.44
3	80.44	0.93(80.44) = 74.81
4	74.81	69.57
5	69.57	64.70
6	64.70	60.17
7	60.17	55.96
8	55.96	52.04
9	52.04	48.40
10	48.40	45.01

Step 2. Use the data in Table 2 to create a graph of mass remaining versus time (**Figure 2**).

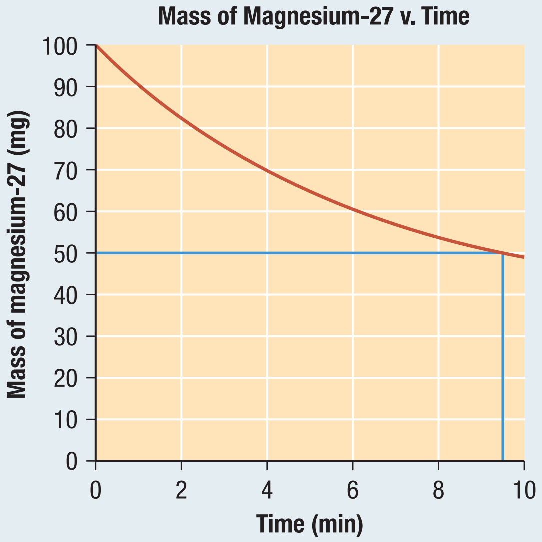

Figure 2

Step 3. Use the data in Table 2 and the graph in Figure 2 to determine the half-life of magnesium-27. Half of the initial mass of magnesium-27 has decayed approximately halfway between 9 min and 10 min. So, the half-life of magnesium-27 is about 9.5 min.

Step 4. Model the decay algebraically by substituting the half-life of 9.5 min into the half-life decay equation (note that time is measured in minutes, not seconds or hours):

$$A = A_0\left(\frac{1}{2}\right)^{\frac{t}{h}}$$

$$A = A_0\left(\frac{1}{2}\right)^{\frac{t}{9.5}}$$

Practice

1. Aluminum-30 has a half-life of 3.6 s. T/I C
   (a) What percent of an initial sample will remain after 10 s? [ans: 15 %]
   (b) What percent of an initial sample will remain after 10 min? [ans: 6.7×10^{-49} %]
2. After 10 years, a 100 mg sample of argon-42 has decayed to 81 mg. Estimate the half-life of argon-42. T/I C [ans: 33 years]

Applications of Half-Life: Carbon Dating

The half-life of carbon-14 is 5730 years. It decays into nitrogen-14 according to the following nuclear reaction equation:

$${}^{14}_{6}\text{C} \rightarrow {}^{14}_{7}\text{N} + {}^{0}_{-1}\text{e}$$

The half-life of C-14 makes it a useful material for measuring the age of organisms that once lived long ago. When plants absorb carbon dioxide through the process of photosynthesis, the carbon is typically a mixture of the common C-12 and the relatively rare C-14 isotopes. Herbivores ingest C-14 when they eat plants, and carnivores do so when they feed on herbivores. The ratio of C-14 to C-12 is generally constant and equal in all living things. When an organism dies, however, it no longer consumes food, and therefore no longer ingests carbon. As the carbon-14 decays, the C-14 to C-12 ratio in the dead organism is reduced by half every 5730 years. Scientists can use this known rate of decrease to determine when the organism died. **Figure 3** shows the percentage of C-14 remaining from an initial mass present as a function of time after an organism dies.

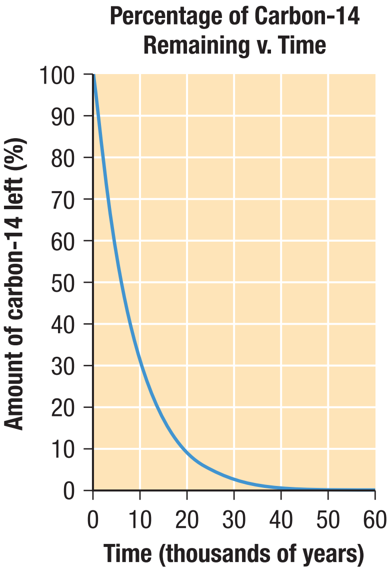

Figure 3 Decay curve for C-14

WEB LINK

To learn more about carbon dating,

GO TO NELSON SCIENCE

Other isotopes are also useful for dating objects and organisms. Aluminum-26, for example, has been used to measure the ages of interstellar rocks. Al-26 decays into magnesium-26 with a half-life of approximately 720 000 years. Scientists can approximate the age of a sample by comparing the relative masses of Al-26 and Mg-26, in a similar way as with carbon dating.

7.3 Summary

- The half-life of a radioactive isotope is the amount of time required for it to decay to one-half of its original mass.
- Half-lives can vary from a tiny fraction of a second to millions of years.
- The decay of a radioactive isotope can be mathematically modelled using a table, a graph, or an equation.
- Some isotopes like carbon-14 and aluminum-26 have useful applications due in part to their particular half-lives.
- Carbon-14 is a useful isotope for dating fossils and other archaeological objects.

7.3 Questions

1. Chlorine-38, which undergoes beta-negative decay, has a half-life of 37.24 min. K/U T/I C
    (a) Construct a table that compares the mass of Cl-38 remaining after *t* minutes for several values of *t*.
    (b) Draw a graph that illustrates this relationship.
    (c) What isotope does Cl-38 decay into?
2. Gold-198, with a half-life of 2.6 days, is used to diagnose and treat liver disease. T/I C
    (a) Write a half-life decay equation that relates the mass of Au-198 remaining to time in days.
    (b) What percentage of a sample of Au-198 would remain after
        (i) 1 day?
        (ii) 1 week?
3. Cobalt-60, with a half-life of 5.3 years, has a number of applications, including medical therapy and the sterilization of medical tools. Determine the mass of a 50 g sample that would remain after
    (a) 6 months
    (b) 5 years T/I C
4. What type of radioactive decay is involved in carbon dating? Explain the process of carbon dating. K/U C
5. A fossil contains 70 % of the carbon-14 it once had as a living creature. Use the half-life decay equation to determine when the creature died. T/I C

Aluminum-26, which decays into magnesium-26, has a half-life of approximately 720 000 years. Use this information to answer Questions 6 and 7.

6. (a) What type of decay does Al-26 undergo?
    (b) Does Al-26 decay in the same way as C-14? Explain. K/U C
7. A moon rock has 3 % of its original Al-26 mass. K/U T/I C
    (a) Determine the age of the moon rock.
    (b) Discuss any assumptions that must be made when using this method of dating.
8. Take a regular sheet of paper. Measure its length and width and determine the area. Fold the paper neatly in half. Determine the new area. Repeat until you cannot fold the paper any longer. Explain how this model can be used to describe half-life. K/U C

7.4 Nuclear Fission and Nuclear Power Generation

When Ernest Rutherford split the atom for the first time in 1919, few would have predicted how profoundly our world would change. The footprint of the nuclear revolution of the twentieth century can be found in areas ranging from medical advances that save lives, to nuclear power, to devastating weaponry.

Figure 1 CANDU reactor facility

Nuclear power generation is controversial. Nuclear power reactors emit virtually no pollutants into the atmosphere, yet they produce harmful radioactive waste that must be safely contained and stored for long periods of time. Opponents of nuclear power cite the dangers of reactor meltdowns. However, Canada's reactors have impressive safety records. Nuclear energy is a critical part of our power supply. Over 50 % of Ontario's electric power is generated from Canadian Deuterium Uranium reactors, or CANDU reactors, as they are commonly called (**Figure 1**).

The process by which a nuclear reactor operates is based on the work of Albert Einstein, whose theory of relativity consists of a number of abstract ideas. One of these is that mass and energy are actually different aspects of the same phenomenon.

Mass–Energy Equivalence

In the early twentieth century, Einstein proposed what is arguably the most famous equation in science:

$$E = mc^2$$

This equation challenged the foundations of physics by suggesting that energy and mass are equivalent. The equation states that the energy, E, of an object at rest is equal to its mass, m, multiplied by the speed of light, c, squared. The speed of light is 3.0×10^8 m/s.

As Einstein's theory became widely accepted, the notions of conservation of mass and conservation of energy were replaced by the more general law of conservation of mass–energy.

Law of Conservation of Mass–Energy

Mass can transform into energy, and energy into mass, such that the total mass–energy in an isolated system remains constant.

An isolated system is a system that is free from outside influences. No energy flows into or out of the system, and no mass is added or removed from the system. It is this relationship between mass and energy that can help explain the vast amount of energy that is released during a nuclear reaction, as you will see in Tutorial 1.

atomic mass unit (u) a unit of mass equal to 1.66×10^{-27} kg

The atomic mass unit is commonly used in chemistry and physics as a more convenient unit of mass than the kilogram. One **atomic mass unit (u)** is equal to the mass of one-twelfth of a carbon-12 atom, or 1.66×10^{-27} kg. **Table 1** lists the masses of subatomic particles in kilograms and in atomic mass units.

Table 1 Masses of Subatomic Particles

Particle	Mass (kg)	Mass (u)
proton	$1.672\,614 \times 10^{-27}$	1.007 276
neutron	$1.674\,920 \times 10^{-27}$	1.008 665
electron	$9.109\,56 \times 10^{-31}$	0.000 549

Einstein's equation allows for a deeper understanding of the nucleus. A chart of the nuclides is a chart that lists the atomic number and mass number for every known isotope. If you compare the mass number of an atom on the nuclide chart to the calculated mass of all the atom's nucleons and electrons, you will notice a **mass defect**. The sum of the masses of the nucleons and electrons of an atom is always slightly greater than the actual atomic mass. The "missing mass" exists in the form of energy, which is used to hold the nucleus together. This **binding energy** is the amount of energy that would be needed to separate all of the nucleons of an atom's nucleus.

mass defect the difference between the calculated mass of an atom, based on the nucleons and electrons present, and the actual atomic mass

binding energy the energy used to hold a nucleus together

WEB **LINK**

To learn more about Einstein's work,

GO TO NELSON SCIENCE

In nuclear physics, the joule is not a very convenient unit of measure to use for energy. Instead, a much smaller unit, called the mega-electron volt (MeV), is more useful. An electron-volt (eV) is defined as the amount of energy given to an electron when it is accelerated through a potential difference of 1 V. One electron-volt is equal to 1.602×10^{-19} J. The **mega-electron volt** is one million times this value:

$$1 \text{ MeV} = 1.602 \times 10^{-13} \text{ J}$$

mega-electron volt (MeV) the energy required to accelerate an electron through a potential difference of 1 million volts

In the following Tutorial, you will determine the mass defect of a parent atom in a nuclear fission reaction and then use Einstein's equation to calculate the energy released during the reaction.

Tutorial **1** Calculating the Mass Defect and Binding Energy

We can calculate the mass defect of a nucleus by comparing the total mass of its nucleons and electrons to the actual atomic mass. Note that we will use Δm to represent the *difference* in mass. Once the mass defect is known, we can use Einstein's equation to calculate the corresponding binding energy. We will use this strategy in the following Sample Problem.

Sample Problem 1

Determine the mass defect and binding energy of a lithium-7 nucleus, given that its actual atomic mass is 7.016 00 u. Use Table 1 on the previous page.

Given: $m = 7.016\ 00$ u

Required: mass defect; E

Analysis: $E = \Delta mc^2$

Solution: First use Table 1 to calculate the combined mass of the individual protons, neutrons, and electrons. The actual atomic mass is given. The difference between these quantities is the mass defect. Since the mass defect is related to the binding energy, use $E = \Delta mc^2$ to calculate the binding energy, Δm. A lithium-7 atom has three protons, four neutrons, and three electrons. Calculate the total mass of these subatomic particles.

$$\begin{aligned} 3m_p + 4m_n + 3m_e &= 3(1.007\ 276 \text{ u}) + 4(1.008\ 665 \text{ u}) + 3(0.000\ 549 \text{ u}) \\ &= 7.058\ 135 \text{ u} \end{aligned}$$

Subtract the actual atomic mass of Li-7 to calculate the mass defect, Δm.

$$\Delta m = 7.058\ 135 \text{ u} - 7.016\ 00 \text{ u}$$

$$\Delta m = 0.042\ 135 \text{ u}$$

Therefore, the mass defect of lithium-7 is 0.042 135 u.

Multiply the mass defect by 1.66×10^{-27} kg/u to convert atomic mass units to kilograms.

$$\begin{aligned} \Delta m &= (0.042\ 135\ \cancel{\text{u}})\left(1.66 \times 10^{-27}\ \frac{\text{kg}}{\cancel{\text{u}}}\right) \\ &= 6.994\ 4 \times 10^{-29} \text{ kg (two extra digits carried)} \end{aligned}$$

Substitute 6.9944×10^{-29} kg and the speed of light (3.0×10^{8} m/s) into $E = \Delta mc^2$.

$$\begin{aligned} E &= (6.9944 \times 10^{-29}\ \text{kg})(3.0 \times 10^{8}\ \text{m/s})^2 \\ &= 6.2950 \times 10^{-12}\ \text{kg}\cdot\text{m}^2/\text{s}^2 \text{ (three extra digits carried)} \\ &= 6.2950 \times 10^{-12}\ \text{J} \end{aligned}$$

The binding energy of a lithium-7 nucleus is 6.2950×10^{-12} J.

We can convert this to MeV by dividing by the number of joules in a mega-electron volt:

$$E = \frac{6.2950 \times 10^{-12}\ \cancel{\text{J}}}{1.602 \times 10^{-13}\ \dfrac{\cancel{\text{J}}}{\text{MeV}}}$$

$$E = 39\ \text{MeV}$$

Statement: The mass defect of Li-7 is 0.042 135 u. The binding energy of the nucleus is 39 MeV.

Practice

1. The mass of a helium-4 atom is 4.002 603 u. T/I C
   - (a) Determine the mass defect of a helium-4 atom. [ans: 0.030 378 u]
   - (b) Determine the binding energy of a helium-4 atom. Give your final answer in MeV. [ans: 28 MeV]

Nuclear Fuel

Nuclear fuel is the radioactive material that is used to power a nuclear reactor. When nuclear fission occurs, the binding energy of a nucleus is released and is converted into a useful form of energy. Some radioactive isotopes with very large mass numbers undergo nuclear fission when struck by a neutron. For example, uranium-235 can be split into krypton-92 and barium-141, as shown in **Figure 2**.

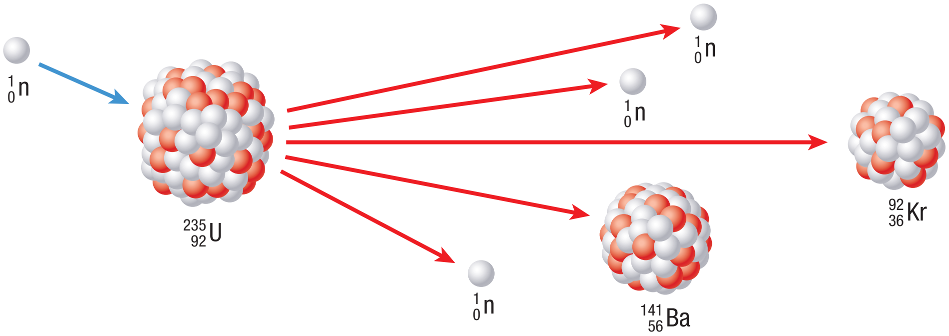

Figure 2 Nuclear fission of uranium-235

The equation for this nuclear reaction is

$$^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{92}_{36}\text{Kr} + {}^{141}_{56}\text{Ba} + 3({}^{1}_{0}\text{n}) + \text{energy}$$

Parent isotopes such as U-235 that can undergo nuclear fission are said to be fissionable. Some other examples of fissionable isotopes are thorium-232, uranium-233, and plutonium-239. Fissionable isotopes are the nuclear fuel used in nuclear fission reactors.

The large quantity of energy produced during each nuclear reaction makes nuclear fission desirable for power generation. In comparison, the amount of energy produced in a nuclear fission reaction is about seven million times as great as the energy released when the same mass of dynamite explodes.

WEB **LINK**

To see a simulation of this nuclear fission reaction,

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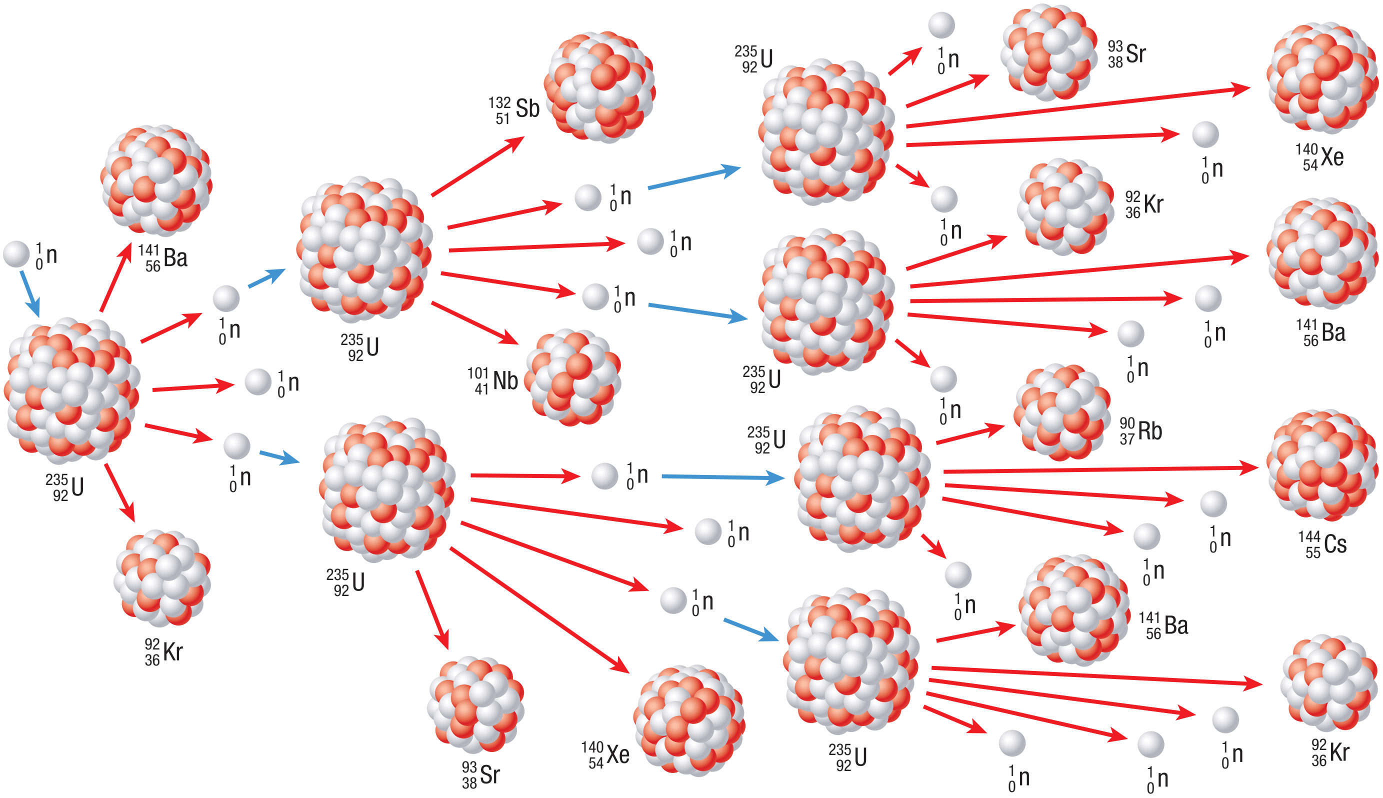
Chain Reactions

The products of the nuclear fission reaction shown in Figure 2 on the previous page include three neutrons and energy. Not only is a very large quantity of energy released, but some of the neutrons produced in the reaction are used to generate further reactions. If enough fuel is present, a chain reaction can occur. A **chain reaction** is a series of reactions that can repeat over several cycles (**Figure 3**). These reactions occur without requiring any material being added to the system. The products of one reaction produce subsequent reactions. The amount of nuclear fuel required to cause a chain reaction is called the critical mass.

chain reaction the repeated series of reactions in which the products of one reaction generate subsequent reactions



$^{1}_{0}$n
$^{141}_{56}$Ba
$^{235}_{92}$U
$^{92}_{36}$Kr
$^{1}_{0}$n
$^{1}_{0}$n
$^{1}_{0}$n
$^{235}_{92}$U
$^{132}_{51}$Sb
$^{1}_{0}$n
$^{1}_{0}$n
$^{1}_{0}$n
$^{101}_{41}$Nb
$^{235}_{92}$U
$^{1}_{0}$n
$^{1}_{0}$n
$^{1}_{0}$n
$^{93}_{38}$Sr
$^{140}_{54}$Xe
$^{235}_{92}$U
$^{1}_{0}$n
$^{93}_{38}$Sr
$^{140}_{54}$Xe
$^{1}_{0}$n
$^{92}_{36}$Kr
$^{1}_{0}$n
$^{235}_{92}$U
$^{1}_{0}$n
$^{141}_{56}$Ba
$^{1}_{0}$n
$^{1}_{0}$n
$^{235}_{92}$U
$^{1}_{0}$n
$^{90}_{37}$Rb
$^{144}_{55}$Cs
$^{1}_{0}$n
$^{1}_{0}$n
$^{235}_{92}$U
$^{1}_{0}$n
$^{141}_{56}$Ba
$^{1}_{0}$n
$^{1}_{0}$n
$^{1}_{0}$n
$^{92}_{36}$Kr

Figure 3 Chain reaction induced by the fission of U-235

Neutron Moderation

The neutrons that are released from the fission of U-235 are initially too high in energy to be absorbed by another U-235 nucleus. They must be slowed down, or moderated. In a CANDU reactor, neutrons are moderated by surrounding the fuel elements with heavy water, which is water that contains a high level of deuterium. Heavy water also reduces neutron leakage from a reactor core. Heavy water is about 11 % denser than normal water.

Neutrons that have been slowed down using heavy water are called thermal neutrons because their kinetic energy is at about the same level as the other materials around them. Once a high-energy neutron has been moderated, it can be absorbed by another U-235 nucleus, eventually establishing a chain reaction. Examples of fissionable materials that can sustain a chain reaction are uranium-235 and plutonium-239. In the following Tutorial, you will calculate the energy released during a nuclear fission reaction.

WEB **LINK**

CANDU reactors are used in many parts of the world. They are considered one of the safest fission reactors. To learn more about CANDU reactors,

GO TO NELSON SCIENCE

Tutorial 2 Calculating Energy Yield in a Fission Reaction

We can calculate the energy released in a fission reaction by calculating the mass defect between the reactant and the products and then converting this to its energy equivalent using Einstein's equation $E = mc^2$.

Sample Problem 1

What is the energy yield of the following fission reaction? Use the given masses below.

$$^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{140}_{55}\text{Cs} + {}^{93}_{37}\text{Rb} + 3({}^{1}_{0}\text{n})$$

mass of U (m_{U}) = 235.044 u
mass of Cs (m_{Cs}) = 139.909 u
mass of Rb (m_{Rb}) = 92.922 u
mass of neutron (m_{n}) = 1.009 u

Given: $m_{\text{U-235}} = 235.044$ u; $m_{\text{Cs-140}} = 139.909$ u; $m_{\text{Rb-93}} = 92.922$ u; $m_{\text{n}} = 1.009$ u

Required: energy released

Analysis: $E = \Delta mc^2$

Solution: The energy released is equal to the binding energy. So first use the given masses to calculate the difference in mass between the reactant and the products. The difference is the mass defect. Then substitute the mass defect into the equation $E = \Delta mc^2$ to calculate the binding energy. Note that the reaction equation can be simplified by subtracting one neutron from each side:

$$^{235}_{92}\text{U} + {}^{1}_{0}\cancel{\text{n}} \rightarrow {}^{140}_{55}\text{Cs} + {}^{93}_{37}\text{Rb} + \overset{2}{\cancel{3}}({}^{1}_{0}\text{n})$$

$$^{235}_{92}\text{U} \rightarrow {}^{140}_{55}\text{Cs} + {}^{93}_{37}\text{Rb} + 2({}^{1}_{0}\text{n})$$

Calculate the mass defect.

$$\begin{aligned}
\Delta m &= m_{\text{U-235}} - (m_{\text{Cs-140}} + m_{\text{Rb-93}} + 2m_{\text{n}}) \\
&= 235.044\text{ u} - [139.909\text{ u} + 92.922\text{ u} + 2(1.009\text{ u})] \\
&= 235.044\text{ u} - 234.849\text{ u} \\
\Delta m &= 0.1950\text{ u}
\end{aligned}$$

Convert the mass defect to kilograms.

$$\begin{aligned}
0.1950\text{ u} &= 0.1950\,\cancel{\text{u}}\left(1.66 \times 10^{-27}\,\frac{\text{kg}}{\cancel{\text{u}}}\right) \\
&= 3.237 \times 10^{-28}\text{ kg}
\end{aligned}$$

Now determine the binding energy.

$$\begin{aligned}
E &= \Delta mc^2 \\
&= (3.237 \times 10^{-28}\text{ kg})(3.0 \times 10^{8}\text{ m/s})^2 \\
&= 2.91 \times 10^{-11}\ \text{kg·m}^2/\text{s}^2 \\
E &= 2.91 \times 10^{-11}\text{ J}
\end{aligned}$$

Statement: The nuclear fission reaction releases 2.91×10^{-11} J of energy per reaction.

Practice

1. Determine the energy yield of the following fission reaction. Use the given masses below.

$$^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{94}_{40}\text{Zr} + {}^{139}_{52}\text{Te} + 3({}^{1}_{0}\text{n})$$

$m_{\text{Zr-94}} = 93.906$ u

$m_{\text{Te-139}} = 138.935$ u

T/I C [ans: 2.8×10^{-11} J]

CANDU Reactors

A simplified schematic of a CANDU reactor is shown below in **Figure 4**. The calandria, or core, of the reactor is where the fission process occurs. As neutrons and thermal energy are produced, heavy water both moderates neutrons and absorbs thermal energy. As the heavy water flows through the primary loop, thermal energy is transferred to the steam generator. This transfer of energy cools the heavy water, which then flows back into the core to repeat the cycle.

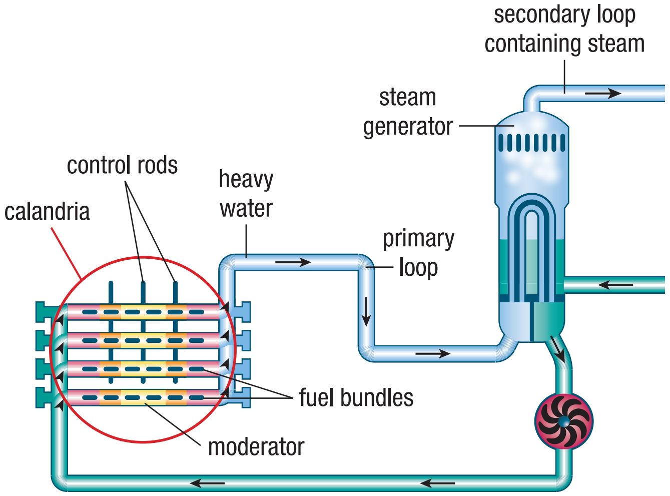


Figure 4 Schematic of a CANDU reactor

calandria core of the reactor, consisting of fuel bundles, control rods, and moderator

fuel bundles fuel elements consisting of uranium pellets

control rods adjustable cadmium rods used to control nuclear reaction rates

moderator heavy water used to slow neutrons and absorb thermal energy

steam generator absorbs thermal energy from the heavy water in the primary loop, producing steam

primary loop closed loop through which heavy water flows

secondary loop closed loop through which normal water, which becomes steam, flows

The steam generator uses the absorbed thermal energy to heat normal water in the secondary loop, producing steam. The steam is sent to a steam turbine, where its high pressure causes the turbine to turn. An electrical energy generator is then used to convert this mechanical energy into electrical energy, which can then be delivered to the electrical power network.

The fission reaction within a CANDU reactor core can be controlled in two ways: coarsely and finely. Cadmium adjuster rods are used for coarse control. The coarse control of the fission reaction is determined by how far the cadmium rods are inserted within the core. To slow the reaction, the rods are inserted farther in. This allows the cadmium to absorb more neutrons. To accelerate the reaction, the rods are moved out of the core to reduce the absorption of neutrons. Liquid zone control compartments are used for fine control.

CANDU Reactor Fuel

CANDU reactors use only natural uranium as fuel. Natural uranium consists of 99.27 % of U-238 and only 0.72 % of U-235, a radioactive isotope. The core consists of a number of fuel bundles, as shown in **Figure 5**. Each fuel bundle consists of several hundred natural uranium pellets. These fuel bundles are responsible for driving the chain reaction within the reactor core.

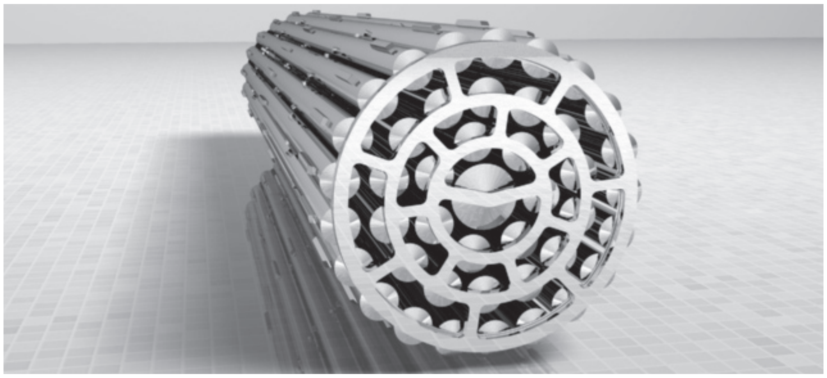


Figure 5 Fuel bundle

CAREER LINK

A nuclear engineer is focused on the safe development and application of nuclear energy. To learn more about careers in the Canadian nuclear industry,

GO TO NELSON SCIENCE

Safety Considerations

Safety is always a concern when dealing with radioactive materials. In a nuclear reactor facility, it is important to ensure that workers are protected from the harmful effects of radiation. Nuclear reactor design engineers must take this into account when choosing materials to shield the reactor core.

Despite all precautions, it is inevitable that workers in a nuclear reactor facility will be exposed to some level of radiation. Tiny levels of radiation exposure are not dangerous. In fact, we are all exposed to background levels of radiation every day. But it is important in a nuclear facility to closely monitor exposure levels and ensure that they are kept within safe limits. For this reason, all workers in a nuclear facility wear badges that indicate their level of radiation exposure. Each badge contains photographic film that becomes exposed when subjected to radiation.

CANDU fission reactors are known worldwide for their safety record. One key design feature is the way that the cadmium shut-off rods are arranged. The rods are inserted into the core vertically from above, suspended by electrically controlled magnets. The rods are dropped into the core to reduce reaction rates, and lifted to increase them. If there is any disruption in electrical power to the reactor, the magnets automatically turn off, causing the rods to drop completely into the core. This immediately stops the chain reaction, ensuring a safe reactor shutdown.

WEB LINK

To learn more about various nuclear waste disposal options,

GO TO NELSON SCIENCE

Waste Disposal

Nuclear reactors emit very small quantities of pollutants into the atmosphere. In addition, radioactive waste must be dealt with. Radioactive waste consists of radioactive by-products of nuclear power generation that are generally not useful for other purposes. These materials must be safely stored in appropriately shielded containers, in some cases for hundreds of years.

Research This

Breeder Reactors

Skills: Researching, Analyzing

One way to obtain rare, but useful, isotopes to use as nuclear fuel is to produce them in a breeder reactor.

1. Research breeder reactors on the Internet or in the library. Write a brief report of your findings or design a poster that includes answers to the following questions.

A. What is a breeding chain? T/I C

B. Provide an example of a breeding chain. Identify the isotope that occurs at each reaction stage. T/I C

C. Write reaction equations for each stage of the breeding chain you provided in B. Identify the type of decay that occurs at each stage. Which of these reactions are transmutations? Explain. T/I C

D. Which isotopes are commonly produced in breeder reactors? T/I C

GO TO NELSON SCIENCE

7.4 Summary

- Albert Einstein was the first person to propose that mass and energy are equivalent and related by $E = mc^2$.
- The law of conservation of mass–energy states that the total of mass–energy in any reaction remains constant.
- Very large amounts of energy are released during a nuclear fission reaction; the amount of released energy is equivalent to the mass defect.
- CANDU fission reactors use only natural uranium as a fuel and heavy water as a moderator.
- Heavy water in a nuclear reactor is used to slow neutrons and absorb thermal energy from the core.
- Nuclear waste disposal is a complex issue whose long-term solution is still under development.

7.4 Questions

1. Determine the energy equivalent, in joules, of
   (a) an electron
   (b) a proton T/I C
2. A small sample of coal, when completely converted to energy, releases 4.5×10^{14} J. Determine the original mass of the coal. Assume that the final mass is zero. T/I C
3. Calculate the energy released in the following nuclear reaction, given the masses indicated: T/I C

   ${}^{236}_{92}\text{U} \rightarrow {}^{232}_{90}\text{Th} + {}^{4}_{2}\text{He}$

   $m_{\text{U-236}} = 236.045\ 562\ \text{u}$

   $m_{\text{Th-232}} = 232.038\ 051\ \text{u}$

   $m_{\text{He-4}} = 4.003\ 603\ \text{u}$
4. Calculate the energy released in the following reaction, given the masses indicated: T/I C

   ${}^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{90}_{38}\text{Sr} + {}^{135}_{54}\text{Xe} + 11({}^{1}_{0}\text{n})$

   $m_{\text{U-235}} = 235.044\ \text{u}$

   $m_{\text{Sr-90}} = 89.908\ \text{u}$

   $m_{\text{Xe-135}} = 134.879\ \text{u}$
5. The following shows the products of a uranium-238 decay series: K/U C

   ${}^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} \rightarrow {}^{234}_{91}\text{Pa} \rightarrow {}^{234}_{92}\text{U} \rightarrow {}^{230}_{90}\text{Th} \rightarrow {}^{226}_{88}\text{Ra}$

   (a) Write a nuclear reaction equation for each stage of this series. Assume that beta decay reactions are beta-negative.
   (b) Identify each reaction by type of decay. Explain your answers.
6. Refer to Question 5. This series of reactions is part of a longer one known as the uranium-lead series. K/U T/I
   (a) Research this series and identify the other reactions involved.
   (b) What is the final stable isotope?
7. Summarize the safety issues related to nuclear fission reactors. K/U C
8. Explain how CANDU reactors are designed to minimize danger due to electrical power loss. K/U C
9. The following illustrates the breeding chain used to produce plutonium-239 from uranium-238 in a breeder reactor. The process is initiated by bombarding U-238 with high-energy neutrons:

   ${}^{238}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{239}_{92}\text{U} \rightarrow {}^{239}_{93}\text{Np} \rightarrow {}^{239}_{94}\text{Pu}$

   Classify the nuclear reactions occurring at each stage of this breeding cycle as alpha decay, beta decay, or electron capture. Then write a reaction equation for each stage. Assume that beta decay reactions are beta-negative. T/I C
10. Another breeding chain involves the transmutation of thorium-233 to uranium-233. This occurs in three stages: first a neutron is absorbed by a Th-233 nucleus, and then the daughter isotope undergoes beta-negative decay twice. Write the series of nuclear reaction equations for this breeding chain. Identify parent and daughter isotopes and their mass numbers and atomic numbers for each stage. T/I C

7.5 Nuclear Fusion

Figure 1 The Sun is a natural fusion reactor.

nuclear fusion a nuclear reaction in which the nuclei of two atoms fuse together to form a larger nucleus

What powers the stars, such as our Sun (**Figure 1**)? A particular type of nuclear reaction powers the stars, and knowledge of these reactions can help us understand how stellar objects are formed and how they die. These reactions can also potentially provide society with a clean, renewable source of power. Unlike fossil fuel reactors, nuclear fission reactors are very clean in that they emit very small quantities of pollutants into the atmosphere. However, fission reactors have some negative environmental effects. The radioactive waste products are potentially harmful if not disposed of properly. This has led scientists to seek a cleaner source of power in the form of nuclear fusion. **Nuclear fusion** is a nuclear reaction in which the nuclei of two atoms fuse to form another element. Nuclear fusion is the opposite process of nuclear fission.

In order for nuclear fusion to occur, the fusing nuclei must have enough kinetic energy to overcome the repulsive electrostatic force between them. This allows the nuclei to get close enough to each other for the strong nuclear force to take effect. This is not an easy task to achieve in the laboratory, much less in a power reactor.

Nuclear Stability

Under what conditions are nuclear fission and nuclear fusion most likely to occur? To understand this, we need to consider the relative stability of heavy and light isotopes. **Figure 2** shows the binding energy per nucleon of all stable elements. The higher the binding energy value, the more stable is the nucleus.

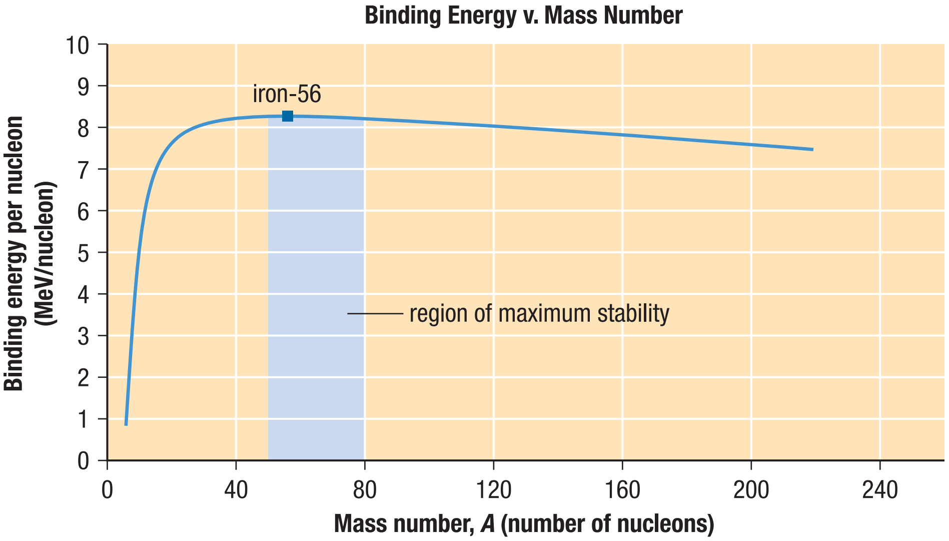


Figure 2 Binding energy as a function of mass number

Notice that this binding energy graph rises sharply, reaching a maximum at $A = 56$, before gradually decreasing. This suggests that iron-56 is the most stable of all nuclei, with the most tightly bound nucleus.

Consider the right side of the graph: the heavier nuclei. When a heavy nucleus undergoes nuclear fission, the nuclei of the daughter atoms typically have mass numbers that average around 118, which is closer to the region of maximum stability. The binding energy of the daughters of a fission reaction is therefore greater than that of the parent. The products are more stable than the reactant.

Consider the left side of the graph: the lighter nuclei. When these atoms fuse together to form a heavier nucleus, the binding energy increases sharply, with the reaction again producing a product that is closer to the region of maximum stability. The product is more stable than the reactants.

Nuclear fission is more likely to occur with very heavy nuclei, while nuclear fusion is more likely to occur with very light nuclei. In both situations, the total binding energy increases during the reaction. This implies that the mass defect has increased, which corresponds to a release of energy. Both fission and fusion reactions are highly exothermic.

By calculating the energy released in each type of reaction, you can accurately compare the relative energy output of a nuclear fusion reaction with that of a nuclear fission reaction. It is important to consider the energy equivalent of one atomic unit of mass, measured in MeV:

$$\begin{aligned} E &= mc^2 \\ &= (1.66 \times 10^{-27}\ \text{kg})(3.0 \times 10^{8}\ \text{m/s})^2 \times \frac{1\ \text{MeV}}{1.602 \times 10^{-13}\ \text{J}} \\ &= 930\ \text{MeV} \end{aligned}$$

Since this is the energy of 1 atomic mass unit (1 u), we can use

$mc^2 = (1\ \text{u})c^2 = 930\ \text{MeV}$ or $(1\ \text{u})c^2 = 930\ \text{MeV}$

Dividing both sides by 1 u gives another way to represent c^2:

$c^2 = 930\ \text{MeV/u}$

In the following Tutorial, you will determine the mass defect and use it to calculate the energy produced during a fusion reaction and a fission reaction.

LEARNING **TIP**

Unit Analysis
Use unit analysis to simplify the units in this equation: 1 $\text{kg}\cdot\text{m}^2/\text{s}^2$ is equal to 1 J. The joules will divide out, leaving MeV as the unit of energy.

Tutorial 1 Using the Mass Defect to Compare the Energy Output of Fusion and Fission Reactions

Sample Problem 1

Determine the energy released when a deuterium atom (D) fuses with a tritium atom (T) to form helium, according to the nuclear reaction equation below. Use the given masses.

$${}^{2}_{1}\text{H} + {}^{3}_{1}\text{H} \rightarrow {}^{4}_{2}\text{He} + {}^{1}_{0}\text{n} + \text{energy}$$

$m_D = 2.014\ 10\ \text{u}$

$m_T = 3.016\ 05\ \text{u}$

$m_{He} = 4.002\ 60\ \text{u}$

$m_n = 1.008\ 67\ \text{u}$

$c^2 = 930\ \text{MeV/u}$

Given: $m_D = 2.014\ 10\ \text{u}$; $m_T = 3.016\ 05\ \text{u}$; $m_{He} = 4.002\ 60\ \text{u}$; $m_n = 1.008\ 67\ \text{u}$; $c^2 = 930\ \text{MeV/u}$

Required: E

Analysis: $E = \Delta mc^2$

Solution: In this problem, the masses of the parent and daughter atoms of a fusion reaction are given. Since the mass defect is related to the binding energy, use $E = \Delta mc^2$ to calculate the energy released. First, calculate the mass defect, Δm.

$$\begin{aligned} \Delta m &= (m_D + m_T) - (m_{He} + m_n) \\ &= (2.014\ 10\ \text{u} + 3.016\ 05\ \text{u}) - (4.002\ 60\ \text{u} + 1.008\ 67\ \text{u}) \\ &= 5.030\ 15\ \text{u} - 5.011\ 27\ \text{u} \\ \Delta m &= 0.018\ 88\ \text{u} \end{aligned}$$

Substitute 0.018 88 u into $E = \Delta mc^2$ to determine the binding energy.

$$\begin{aligned} E &= \Delta mc^2 \\ &= (0.018\ 88\ \text{u})(930\ \text{MeV/u}) \\ E &= 17.6\ \text{MeV} \end{aligned}$$

Statement: 17.6 MeV of energy is released when a deuterium atom fuses with a tritium atom to form helium.

Sample Problem 2

Determine the energy released when uranium-235 produces tellurium-140 and zirconium-94, according to the nuclear fission reaction equation below. Use the given masses.

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{140}_{52}\mathrm{Te} + {}^{94}_{40}\mathrm{Zr} + 2({}^{1}_{0}\mathrm{n}) + \text{energy}$$

$$\begin{aligned} m_{\text{U-235}} &= 235.043\ 9\ \text{u} \\ m_{\text{Te-140}} &= 139.938\ 9\ \text{u} \\ m_{\text{Zr-94}} &= 93.906\ 3\ \text{u} \\ m_{\text{n}} &= 1.008\ 67\ \text{u} \\ \text{c}^2 &= 930.0\ \text{MeV/u} \end{aligned}$$

Given: $m_{\text{U-235}} = 235.0439$ u; $m_{\text{Te-140}} = 139.938\ 9$ u; $m_{\text{Zr-94}} = 93.906\ 3$ u; $m_{\text{n}} = 1.008\ 67$ u; $c^2 = 930.0$ MeV/u

Required: E

Analysis: $E = \Delta mc^2$

Solution: In this problem, the masses of the parent and daughter atoms of a fission reaction are given. Since the mass defect is related to the binding energy, use $E = \Delta mc^2$ to calculate the energy released. Calculate the mass defect. Notice that one neutron can be cancelled on either side of the reaction equation.

$$^{235}_{92}\mathrm{U} + \cancel{{}^{1}_{0}\mathrm{n}} \rightarrow {}^{140}_{52}\mathrm{Te} + {}^{94}_{40}\mathrm{Zr} + \cancel{2}({}^{1}_{0}\mathrm{n}) + \text{energy}$$

$$^{235}_{92}\mathrm{U} \rightarrow {}^{140}_{52}\mathrm{Te} + {}^{94}_{40}\mathrm{Zr} + {}^{1}_{0}\mathrm{n} + \text{energy}$$

$$\begin{aligned} \Delta m &= m_{\text{U-235}} - (m_{\text{Te-140}} + m_{\text{Zr-94}} + m_{\text{n}}) \\ &= 235.043\ 9\ \text{u} - (139.938\ 9\ \text{u} + 93.906\ 3\ \text{u} + 1.008\ 67\ \text{u}) \\ \Delta m &= 0.190\ 030\ \text{u} \end{aligned}$$

Substitute 0.190 030 u into $E = \Delta mc^2$ to determine the binding energy.

$$\begin{aligned} E &= \Delta mc^2 \\ &= (0.190\ 030\ \text{u})(930.0\ \text{MeV/u}) \\ E &= 176.7\ \text{MeV} \end{aligned}$$

Statement: 176.7 MeV of energy is released when U-235 undergoes fission to produce Te-140 and Zr-94.

Practice

1. One type of stellar fusion reaction is the burning of helium to form carbon. The reaction equation for this process is

$$^{4}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{12}_{6}\mathrm{C} + \text{energy}$$

The masses of the parent and daughter atoms are $m_{\text{He}} = 4.002\ 60$ u and $m_{\text{C}} = 12.000\ 00$ u. T/I C

(a) Calculate the mass defect for this reaction. [ans: 0.007 80 u]

(b) Determine the energy released in this reaction. [ans: 7.25 MeV]

(c) What is the energy released per nucleon? [ans: 0.60 MeV/nucleon]

The calculations in Tutorial 1 suggest that fission produces more energy than fusion. Note, however, that the uranium-235 in the fission reaction has about 50 times more mass than the reactants in the fusion reaction. So, on a per mass basis, fusion typically yields more energy than fission.

The Quest for Controlled Nuclear Fusion

Achieving nuclear fusion in a laboratory is very difficult. The only natural conditions that allow for nuclear fusion to occur are in the cores of stars, where the pressure, temperature, and density of nuclei are tremendous. Even under such conditions, the probability of a nuclear fusion reaction occurring is low. Successful fusion reactions occur only because of the huge number of interactions.

Stellar Fusion

In the cores of stars, temperatures and pressures can build to the high levels necessary for fusion. Two of the processes in which stellar fusion occurs are described below.

PROTON-PROTON CHAIN

Fusion occurs in stars the size of the Sun and smaller through a process called the proton-proton chain. In this series of reactions, four protons eventually fuse to form one helium-4 atom. The net reaction in a proton-proton chain can be described by the following equation:

$$4({}^{1}_{1}\mathrm{H}) \rightarrow {}^{4}_{2}\mathrm{He} + 2({}^{0}_{+1}\mathrm{e}) + \text{energy}$$

Notice that two of the four protons each becomes a neutron and a positron. Conversion of hydrogen to helium in the core of a star is just the first step in the production of all of the naturally occurring elements listed in the periodic table. In this sense, stars can be thought of as the factories of all matter. The process of forming larger elements from smaller ones via nuclear fusion is known as nucleosynthesis.

CARBON-NITROGEN-OXYGEN CYCLE

Another process occurs in stars that are significantly larger, and hotter, than the Sun. The carbon-nitrogen-oxygen cycle activates the fusion of hydrogen into helium. In this cycle, a carbon-12 nucleus undergoes a number of nuclear reactions involving fusion and decay. A summary of these is shown below. Notice that this cycle begins and ends with a carbon-12 atom.

$${}^{12}_{6}\mathrm{C} \rightarrow {}^{13}_{7}\mathrm{N} \rightarrow {}^{13}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} \rightarrow {}^{15}_{8}\mathrm{O} \rightarrow {}^{15}_{7}\mathrm{N} \rightarrow {}^{12}_{6}\mathrm{C} + {}^{4}_{2}\mathrm{He}$$

This series of nuclear reactions produces large quantities of energy. The high energy yield of the carbon-nitrogen-oxygen cycle has motivated scientists to develop technologies for producing controlled nuclear fusion. However, another important factor makes nuclear fusion better than fission from an environmental standpoint. Nuclear fission reactors produce radioactive waste that is potentially harmful to humans and the environment. During the process of nuclear fusion, far less radioactive waste is produced. Theoretically, nuclear fusion is our cleanest potential source of energy.

Modern Advances in Nuclear Fusion

MAGNETIC CONFINEMENT FUSION

One of the most promising methods for controlling nuclear fusion is based on the principle of magnetic confinement. Deuterium and tritium are placed in the core of the reactor and heated to an extremely high temperature, comparable to that of the Sun's core. When this happens, the materials change to the fourth state of matter, called plasma. Plasma is the fluid state of matter in which all atoms are ionized. These are the required conditions for nuclear fusion to occur.

The challenge, however, is how to confine matter that is in such a high thermal energy state. In the Sun, the enormous attractive gravitational forces due to its immense mass are sufficient to confine the plasma. This is not practical, however, for the masses of fuels suited to a laboratory or reactor.

LEARNING **TIP**

Superconducting Electromagnets

A superconductor is a material with little to no electrical resistance. A superconducting electromagnet produces powerful magnetic fields when current is applied. You will learn more about electromagnets in Chapter 13.

To achieve plasma confinement under laboratory conditions, a superconducting electromagnet is placed around the core in the shape of a toroid (donut shape) as shown in **Figure 3**. When a high current is passed through the coil, a very powerful magnetic field is produced, which confines the plasma.

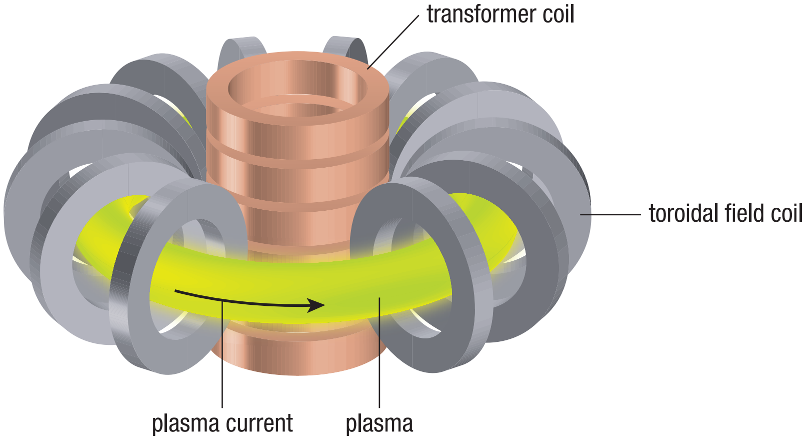


Figure 3 Magnetic confinement fusion reactor design

Theory suggests that with the plasma state achieved, and the fuel magnetically confined, fusion can occur, resulting in the release of energy. While there have been some reports of successful trials of controlled nuclear fusion in laboratory conditions, none have yet been achieved that can sustain a chain reaction. This is the ultimate goal that must be achieved if we are to use nuclear fusion as a practical energy source.

THE ITER PROJECT

The ITER project is an international joint effort aimed at developing a functional nuclear fusion reactor for research purposes. (Iter means ″the way″ in Latin.) The ITER reactor in Cadarache, France, is a type of magnetic confinement fusion reactor called a Tokamak (**Figure 4**). This very expensive project has provoked controversy from skeptics who feel that too much money will be wasted with little return on investment. Canada, originally a participant, has withdrawn due to lack of funding. Critics of the project also voice objections to the experimental nature of the facility.

WEB LINK

To learn more about the ITER Tokamak reactor,

GO TO NELSON SCIENCE

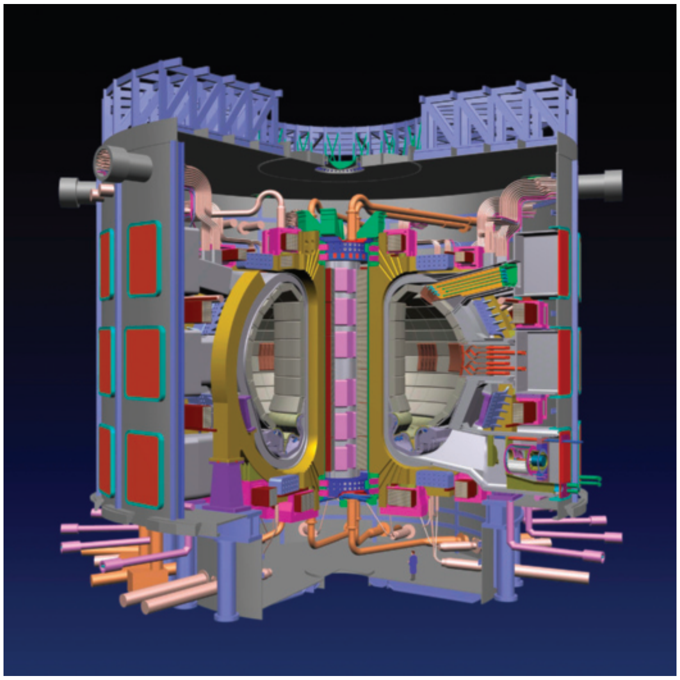


Figure 4 ITER Tokamak reactor design

7.5 Summary

- Nuclear fusion is the process by which lighter atoms fuse together to form heavier atoms.
- Nuclear fusion reactions are exothermic and produce significantly more energy per mass of fuel than fission reactions.
- Nuclear fusion is a potential source of clean energy, producing little pollution or waste.
- Magnetic confinement fusion is a method in which electromagnetic forces are used to confine fusion fuel that is in a very high-temperature, plasma state.
- Controlled nuclear fusion has been achieved, but not in a sustainable way.
- The ITER project is the first significant international attempt to create a functioning nuclear fusion research reactor.

Investigation 7.5.1

Nuclear Energy: Benefit or Hazard? (p. 350) Now that you have learned about nuclear fission and nuclear fusion, you can perform Investigation 7.5.1. You will explore public opinion on the issue of nuclear energy. You will conduct research, analyze data, and present your findings.

7.5 Questions

1. Compare and contrast nuclear fission and nuclear fusion. How are these reactions alike? How are they different? K/U C
2. (a) Explain why nuclear fusion is more difficult to achieve than nuclear fission.
   (b) Why is nuclear fusion more desirable than nuclear fission for power generation? K/U C
3. Use the following values to answer (a) and (b): T/I C

   $m_{\text{H-1}} = 1.007\ 825\ \text{u}$

   $m_{\text{C-12}} = 12.000\ 00\ \text{u}$

   $m_{\text{C-13}} = 13.003\ 35\ \text{u}$

   $m_{\text{N-14}} = 14.003\ 07\ \text{u}$

   (a) Determine the amount of energy released in the third stage of the carbon-nitrogen-oxygen cycle:

   $${}^{13}_{6}\text{C} + {}^{1}_{1}\text{H} \rightarrow {}^{14}_{7}\text{N} + \text{energy}$$

   (b) In the first stage of the carbon-nitrogen-oxygen cycle, 1.95 MeV is produced per reaction:

   $${}^{12}_{6}\text{C} + {}^{1}_{1}\text{H} \rightarrow {}^{13}_{7}\text{N} + \text{energy}$$

   Use this information to determine the mass of nitrogen-13. T/I
4. Refer to Tutorial 1 on page 343.
   (a) Determine the energy released per nucleon for the fission and fusion reactions in Sample Problems 1 and 2.
   (b) What is illustrated by comparing these energy values? K/U T/I C
5. Deuterium can be extracted from normal water, and tritium is a waste product of CANDU reactors. What does this suggest about the fuel availability for nuclear fusion reactors? A
6. Consider the carbon-nitrogen-oxygen cycle:

   $${}^{12}_{6}\text{C} \rightarrow {}^{13}_{7}\text{N} \rightarrow {}^{13}_{6}\text{C} \rightarrow {}^{14}_{7}\text{N} \rightarrow {}^{15}_{8}\text{O} \rightarrow {}^{15}_{7}\text{N} \rightarrow {}^{12}_{6}\text{C} + {}^{4}_{2}\text{He}$$

   The first two reaction equations of this cycle are

   $${}^{12}_{6}\text{C} + {}^{1}_{1}\text{H} \rightarrow {}^{13}_{7}\text{N} + \text{energy}$$

   $${}^{13}_{7}\text{N} \rightarrow {}^{13}_{6}\text{C} + {}^{0}_{+1}\text{e} + \text{energy}$$

   (a) Which of these is a fusion reaction? Explain.
   (b) Which of these is a beta decay reaction? What type of beta decay is it? Explain how you know.
   (c) Write the remaining reaction equations for this cycle and classify each by type of nuclear reaction. Assume that the beta decay reactions are of the same type as the one given above. K/U T/I C
7. Perform some research on nuclear fusion techniques. What are some alternative methods for controlling nuclear fusion that have not been discussed in this section? Write a sentence or two to describe how each of these works. Include diagrams to support your explanations. T/I C
8. Conduct research on the ITER project. What advances have been made since the publication of this text? T/I

GO TO NELSON SCIENCE

7.6 Explore Applications of Nuclear Technology

SKILLS MENU

- Researching
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating
- Identifying Alternatives

Pest Control

Insect infestation can be extremely harmful in a variety of direct and indirect ways. Some insects carry and transmit diseases, which can harm, or potentially kill, humans, livestock, or crops. Think about what happens when an entire farm crop is damaged, or when a farmer's livestock is destroyed by disease. The economic and environmental consequences of uncontrolled pests can be devastating.

Chemical pesticides have been used since about the 1940s to control the damaging effects of pests on crops. Since the 1960s, environmentalists have drawn attention to the harmful effects these toxins have on the environment. Some claim that the long-term costs may outweigh the short-term benefits of chemical pest control. In an effort to address these environmental issues, some jurisdictions have now banned the use of chemical pesticides. Scientists, meanwhile, look toward alternative options.

During the 1950s, a parasitic insect known as the screwworm (**Figure 1**) was responsible for destroying many cattle in North America. Screwworm flies lay eggs in animals such as cows. When the larvae hatch, they feed on the animal's flesh. The losses to the beef and dairy industries were devastating. Scientists turned to X-ray technology as an alternative to chemical pesticides to deal with this problem. They used X-rays to sterilize male screwworm flies, so that when they mated, no offspring were produced. This is one of the earliest uses of radiation technology for pest control. While there have been no noticeable negative side effects, the long-term consequences of removing any species from a biological system remain unknown.

The tsetse fly (**Figure 2**) is another pest that has been responsible for transmitting a potentially fatal disease called African trypanosomiasis, more commonly known as sleeping sickness. Prevalent in parts of Africa, this disease is responsible for approximately 40 000 human deaths per year.

Figure 1 The screwworm is one pest that has been eliminated from areas using the sterile insect technique.

Figure 2 The sterile insect technique has also been used to eradicate tsetse fly populations.

The Application

An interesting characteristic of the tsetse fly is that the female typically mates only once in her lifetime. Scientists have used this fact to eradicate tsetse populations on the African island of Zanzibar. Large numbers of male tsetse flies are bred in the laboratory and then sterilized using radiation. These sterile males are then introduced into regions where sleeping sickness occurs. Once a female has mated with a sterile male, she does not reproduce. This method of pest control is called the sterile insect technique (SIT).

Nuclear methods for pest control represent a relatively new field of scientific study, and public awareness is not very high. Some people have voiced objections to using techniques such as SIT. The danger of exposure to nuclear radiation remains a concern whenever dealing with radioactive materials. There are also those who argue against widespread sterilization, claiming that such measures are disruptive to our natural ecological order. As with many applications of nuclear technology, the benefits must be measured against the risks and costs.

Your Goal

To inform the public about the benefits, risks, and costs of nuclear methods of pest control as compared to alternative methods

Research

SKILLS HANDBOOK A5

Identify an area related to nuclear techniques that may require further research or long-term monitoring. Conduct library or Internet research about these techniques for pest control and their alternatives. What are some cases in which nuclear methods for pest control are used that were not described in this section? In each case describe

- the pest
- the danger it poses
- technique(s) used to control the pest
- any negative environmental or ecological effects resulting from the technique
- any unanticipated side effects

WEB **LINK**

To learn more about nuclear pest control,

GO TO NELSON SCIENCE

Summarize

Use these questions to summarize your research:

- How does nuclear pest control work?
- Is it safe?
- Is it a viable alternative to other methods?
- Does everyone have access to these techniques?
- Are there conditions in which these techniques would or would not be preferred?
- What are the benefits, risks, and costs of using nuclear pest control techniques?
- Summarize how nuclear pest control compares to other pest control techniques.

Communicate

Summarize your findings and present them in one of these ways:

- slide presentation
- news article
- video
- brochure
- website
- written report
- wiki
- poster
- another format of your choosing

Investigation 7.5.1 CORRELATIONAL STUDY

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Nuclear Energy: Benefit or Hazard?

Throughout this chapter, you have learned how nuclear energy has been applied in various ways to improve our lives. You have also learned about the hazards and risks associated with using radioactive materials. Whether or not society should continue to use nuclear technology remains a controversial issue, one that you will have the opportunity to explore in this activity. What is the public opinion on uses of nuclear energy? How well-informed are people about the benefits and hazards of nuclear power reactors (**Figure 1**)? Are people generally aware of other applications of nuclear technology, such as medical treatments and carbon dating? Are there any differences in public opinion related to education, gender, or other variables such as nationality? Has public opinion remained constant regarding the nuclear power controversy or has it changed over time?

СТІЙ!
РАДІОАКТИВНІСТЬ
ЗАБОРОНЕНА ЗОНА

Figure 1

Purpose

In this investigation, you will design and carry out a correlational study that provides insight into public awareness and public opinion regarding the uses of nuclear technology.

Variables

SKILLS HANDBOOK A2.3

When conducting a correlational study, you are looking for trends or patterns between two or more variables. For example, you may ask, "Is there a relationship between support for nuclear power generation and education level?" In this case, education level is the independent variable and level of support is the dependent variable. If you explore how public opinion changes over time, then time is the independent variable.

The following are some samples of dependent and independent variables to consider. You can choose from these or use other variables for your study.

- dependent variables: support for nuclear fission reactors, support for investing in nuclear fusion research, attitudes toward nuclear medicine
- independent variables: age, gender, education level, nationality, socio-economic status, time

Study Design

In this correlational study, you will collect and analyze online secondary data related to nuclear issues. Secondary data consist of data that have already been collected for another purpose by someone else, such as the Canadian Energy Research Institute. Once you have collected the data, you will use software to analyze and present your findings.

Equipment and Materials

- Internet access
- library resources
- data analysis software (optional)
- spreadsheet software (optional)
- presentation software (optional)

Procedure

1. Choose a dependent variable and an independent variable to study. Express your topic in the form of a question, such as, “Is there a correlation between education level and support for nuclear power plants?”
2. Find secondary data on the Nelson Science website or from another source of your choice. Look for any trends or patterns. You may wish to adjust your topic slightly depending on data availability and the trends that you discover.

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3. Refine and restate your independent and dependent variables in the form of a question. For example, the question stated in Step 1 could be rewritten as, “Is there a correlation between education level and support for building more nuclear power plants in Canada?”
4. Capture and insert your data into a data analysis or spreadsheet software program. Software tools such as Fathom (dynamic statistics) and spreadsheets are excellent tools for manipulating and analyzing large amounts of data. Examine the data using the following strategies:
   - Create one or more graphs that relate the dependent and independent variables.
   - Identify any trends in the data.
   - Calculate the correlational coefficient, r, for any linear trends (r is a measure of goodness of fit; the closer r is to 1 or -1, the stronger the linear correlation).
   - Identify any outliers (points that do not fit a trend) and discuss the impact of these outliers on the results.

Analyze and Evaluate

(a) To what extent do the data provide an answer to the question that you posed? Explain. T/I C

(b) Identify some unmeasured variables that could have influenced the results. T/I C

(c) Are the data conclusive, or would additional research provide additional information? T/I C

(d) Presentation software is useful for organizing and presenting your findings in a clear and persuasive way. Use presentation software, or another tool, to create a presentation that includes the following: T/I C
- the question that you explored
- identification of the independent and dependent variables
- data you found related to your research, presented in the form of tables, graphs, or other visual organizers
- an answer to the question that you posed (note that your final evaluation may or may not provide a clear answer to the question that you posed)
- identification of other non-measured variables and their potential impact on your findings
- suggestions for further research that could provide additional or related information on your topic

Apply and Extend

(e) How do your friends and family feel about the issue that you researched? Design a brief survey related to the question that you explored in this investigation that you can use to obtain primary data (data that you collect yourself). Then conduct your study with a number of people that you know. C A

(f) Analyze your findings for (e) using the tools and strategies you used in the Procedure. Compare and contrast these results to those you obtained based on the secondary data obtained online. Account for any discrepancies that you observe. T/I C

CHAPTER 7 SUMMARY

Summary Questions

1. Create a study guide based on the points in the margin on page 316. Your study guide may be in written form or in a visual format. For each point, create three or four sub-points that provide further information, relevant examples, explanatory diagrams, or general equations.
2. Look back at the Starting Points questions on page 316. Answer these questions using what you have learned in this chapter. Compare your latest answers with those that you wrote at the beginning of the chapter. Note how your answers have changed.

Vocabulary

proton (p. 318)
neutron (p. 318)
nucleons (p. 318)
electron (p. 318)
ground state (p. 318)
excited state (p. 318)
atomic number (p. 319)
mass number (p. 319)
isotope (p. 319)
radioisotope (p. 320)
radiation (p. 320)
radioactivity (p. 323)
nuclear fission (p. 323)
nuclear reaction (p. 324)
electrostatic force (p. 324)
strong nuclear force (p. 324)
radioactive decay (p. 324)
alpha (α) decay (p. 325)
alpha particle (p. 325)
parent atom (p. 325)
daughter atom (p. 325)
transmutation (p. 325)
beta (β) decay (p. 326)
beta particle (p. 326)
positron (p. 326)
photon (p. 328)
gamma (γ) decay (p. 328)
half-life (p. 330)
atomic mass unit (u) (p. 334)
mass defect (p. 335)
binding energy (p. 335)
mega-electron volt MeV (p. 335)
chain reaction (p. 337)
nuclear fusion (p. 342)

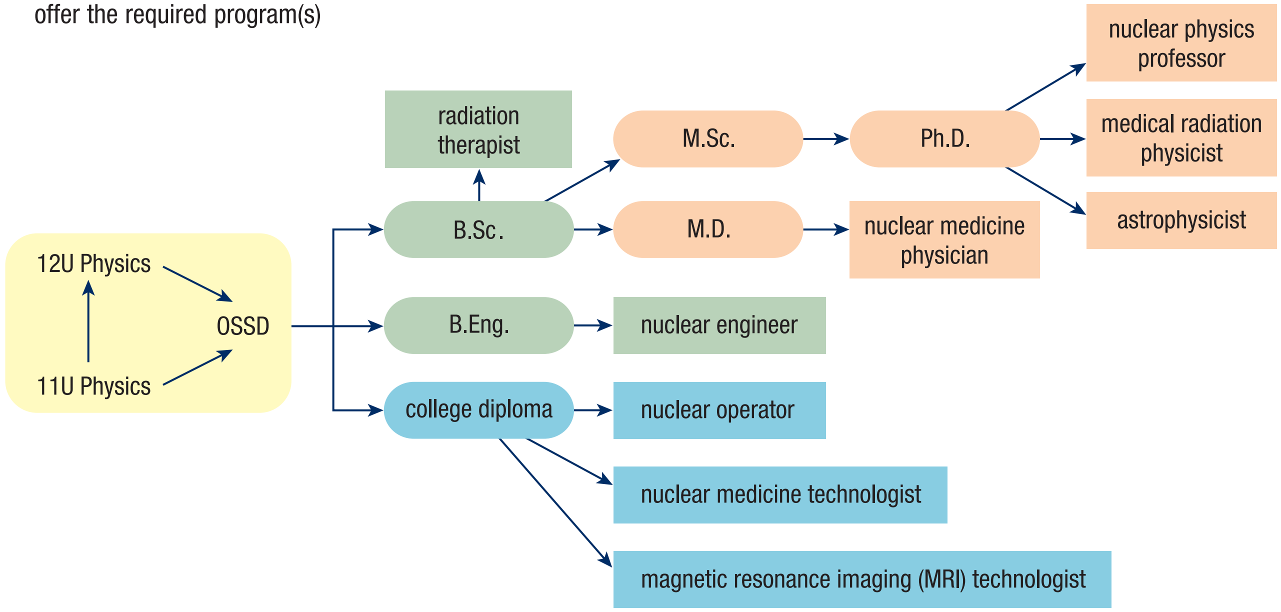
CAREER PATHWAYS

SKILLS HANDBOOK A7

Choose two careers mentioned in this chapter. Research the following information for each:

- educational requirements (secondary and post-secondary, including number of years required, degree(s) obtained, example of courses required)
- two Canadian post-secondary institutions that offer the required program(s)
- skill/personality/aptitude requirements
- potential employers, salary, and duties/responsibilities

Assemble the information into a brochure that compares and contrasts your two chosen careers. Explain how they connect to Nuclear Energy.



nuclear physics professor
radiation therapist
M.Sc.
Ph.D.
medical radiation physicist
astrophysicist
B.Sc.
M.D.
nuclear medicine physician
12U Physics
OSSD
11U Physics
B.Eng.
nuclear engineer
college diploma
nuclear operator
nuclear medicine technologist
magnetic resonance imaging (MRI) technologist

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CHAPTER 7 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. Which of the following ancient Greeks first theorized that all material things were composed of extremely small irreducible particles? (7.1) K/U
   (a) Aristotle
   (b) Socrates
   (c) Democritus
   (d) Euclid
2. Most of an atom consists of
   (a) empty space
   (b) electrons
   (c) protons
   (d) gravity (7.1) K/U
3. Which of the following terms is used to describe the particles in the nucleus of an atom? (7.1) K/U
   (a) electrons
   (b) nucleons
   (c) protozoa
   (d) positrons
4. For atoms in their normal state, which of the following is generally true? (7.1) K/U
   (a) There are more protons than electrons.
   (b) There are fewer protons than electrons.
   (c) The number of protons and electrons are the same.
   (d) The electrons outweigh the nucleons.
5. Which of the following devices is used to accelerate particles to speeds near to that of light? (7.2) K/U
   (a) fission reactor
   (b) accelerometer
   (c) radioactive tracer
   (d) cyclotron
6. When a uranium-238 atom undergoes alpha decay, what is the atomic number of the new isotope? (7.2) T/I
   (a) 92
   (b) 90
   (c) 234
   (d) 242
7. Cobalt-60 has a half-life of 5.27 years. What mass of a 100 mg sample of cobalt-60 will remain in 3.0 years? (7.3) T/I
   (a) 67 mg
   (b) 70 mg
   (c) 72 mg
   (d) 68 mg
8. An electron-volt is defined as
   (a) the amount of charge lost from an electron accelerating through a potential difference of 1 V
   (b) the amount of energy required to accelerate an electron across a potential difference of 1 V
   (c) the amount of energy required to charge an electron
   (d) the amount of energy required to create a potential difference of 1 V (7.4) K/U
9. Which of the following terms is used to describe the combination of two nuclei to form a heavier element? (7.5) K/U
   (a) nuclear fusion
   (b) nuclear fission
   (c) nuclear binding
   (d) nuclear stability

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

10. The nucleus of an atom consists of protons and electrons. (7.1) K/U
11. Electrons can only occupy certain energy levels. (7.1) K/U
12. The mass number of an atom is equal to the number of protons it has. (7.1) K/U
13. An exothermic reaction is a chemical reaction that absorbs energy. (7.2) K/U
14. An unstable atom with a nucleus that can spontaneously disintegrate is said to be radioactive. (7.2) K/U
15. The helium-4 nucleus is called a beta particle. (7.2) K/U
16. Carbon dating uses the half-life of carbon-14 atoms and the known amount of carbon-14 in the environment to determine how long ago an organism died. (7.3) K/U
17. The total mass of all of the particles in a nucleus is the same as the sum of all of their individual masses. (7.4) K/U

To do an online self-quiz,
GO TO NELSON SCIENCE

CHAPTER 7 REVIEW

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

Knowledge

For each question, select the best answer from the four alternatives.

1. Which of the following scientists fired positively charged particles at gold foil and found that some particles scattered? (7.1) K/U
   (a) Dalton
   (b) Bohr
   (c) Rutherford
   (d) Democritus
2. The nucleus of an atom consists of which of the following particles? (7.1) K/U
   (a) protons and electrons
   (b) protons and neutrons
   (c) neutrons and electrons
   (d) protons, neutrons, and electrons
3. Atoms that have electrons in their lowest energy levels are said to be in their
   (a) normal state
   (b) level state
   (c) excited state
   (d) ground state (7.1) K/U
4. How did Becquerel accidentally discover radioactivity? (7.2) K/U
   (a) He placed a sample of uranium on photographic film.
   (b) He left uranium in the cage with a rat.
   (c) He left a piece of plutonium unattended for over a year.
   (d) He noticed that animals exposed to uranium were developing tumours.
5. A reaction in which the nucleus of an atom is split into smaller pieces is known as
   (a) nuclear reduction
   (b) nuclear fusion
   (c) nuclear fission
   (d) atomic separation (7.2) K/U
6. A nuclear reaction that absorbs energy is said to be
   (a) endothermic
   (b) exothermic
   (c) stable
   (d) radioactive (7.2) K/U
7. The half-life of radon-222 is 3.82 days. How much of a 100.0 g sample of radon will be left after one week? (7.3) K/U
   (a) 28.1 g
   (b) 83.4 g
   (c) 50.0 g
   (d) 32.2 g
8. What does an atomic mass unit represent? (7.4) K/U
   (a) $\frac{1}{2}$ of the mass of an isolated hydrogen atom
   (b) the mass of a proton
   (c) $\frac{1}{12}$ of the mass of an isolated carbon-12 atom
   (d) the mass of a neutron
9. The amount of fuel necessary to establish a chain reaction is called the
   (a) reaction mass
   (b) nuclear mass
   (c) fissile material
   (d) critical mass (7.4) K/U
10. What element is the most stable of all nuclides? (7.5) K/U
   (a) iron-54
   (b) iron-56
   (c) manganese-56
   (d) cobalt-56

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

11. The mass number is equal to the number of protons in an atom. (7.1) K/U
12. Elements with different mass numbers but with the same atomic number are said to be different isotopes. (7.1) K/U
13. High-energy particles that are produced by a cyclotron can be useful for medical treatments. (7.2) K/U
14. When a substance undergoes alpha decay, the mass number is reduced by four and the atomic number is reduced by two. (7.2) K/U
15. Beta decay is a nuclear reaction that involves the emission or capture of a positron or an electron. (7.2) K/U
16. Carbon-14 has a half-life of 5730 years and is used in carbon dating to determine the age of fossils. (7.3) K/U

17. Einstein's most famous equation $E = mc^2$ suggests that mass and energy are equivalent. (7.4) K/U

18. CANDU fission reactors use enriched plutonium as fuel. (7.4) K/U

19. Nuclear fusion is the chemical reaction that powers the stars. (7.5) K/U

Match each term on the left with the most appropriate description on the right.

20.

(a)	excited state	(i)	the number of nucleons in an atom
(b)	mass number	(ii)	reaction in which a helium nucleus is emitted from a radioactive element
(c)	isotope	(iii)	when an electron in an atom is in a higher energy level
(d)	radiation	(iv)	versions of the same element but with different mass numbers
(e)	alpha decay	(v)	energy released when an unstable isotope undergoes a structural change
(f)	daughter atom	(vi)	the product atom from a nuclear reaction

(7.1, 7.2) K/U

21. What particle in an atom does not have a charge? (7.1) K/U

22. What is a positron? (7.2) K/U

23. State the law of conservation of mass–energy. (7.4) K/U

24. What is it about a fission reaction that makes the daughter nuclei more stable than the parent nucleus? (7.5) K/U

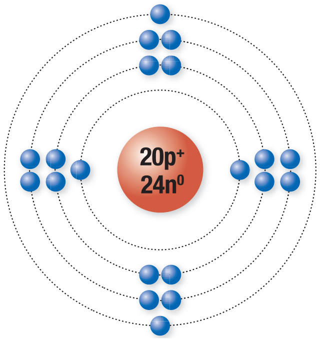
Understanding

25. Use the periodic table to determine the atomic number of each element. Then determine the minimum number of electron shells occupied when each atom is in its normal state. (7.1) K/U
    - (a) beryllium (Be)
    - (b) copper (Cu)
    - (c) argon (Ar)

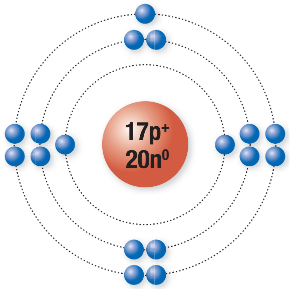
26. Use the periodic table to answer the following questions about potassium-43. The symbol for potassium is K. (7.1) K/U
    - (a) How many protons does this isotope have?
    - (b) How many electrons does this isotope have?
    - (c) How many neutrons are in this isotope?
    - (d) Draw a Bohr–Rutherford diagram for this isotope.

27. Use the Bohr–Rutherford diagrams below to determine each element and its mass number. (7.1) K/U

(a)



(b)



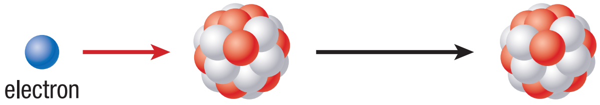
28. (a) Describe how radioisotopes are used for medical diagnosis in the area of nuclear medical imaging.
    (b) Describe one way radioisotopes are used as treatments for diseases. (7.1) K/U

29. For medical testing, why is it important to use radioisotopes with short half-lives? (7.1) K/U

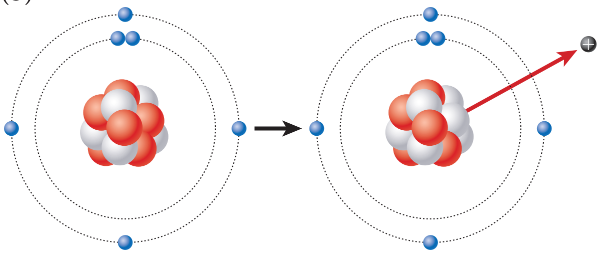
30. (a) Differentiate between chemical and nuclear reactions. In your explanation, include the names of the forces involved, how the reactants and products compare, and the amounts of energy released or absorbed by each.
    (b) In this chapter, you learned about the electrostatic and strong nuclear forces that hold an atom together. Explain how these forces work inside an atom.
    (c) Explain what happens with heavier elements when too many protons are added in the nucleus. (7.2) K/U C

31. The following diagrams show different types of nuclear reactions. Identify the type of nuclear reactions that are occurring in each figure and explain how you know. Red circles represent protons, white circles neutrons, blue circles electrons, black circles positrons, and orange circles photons. (7.2) K/U

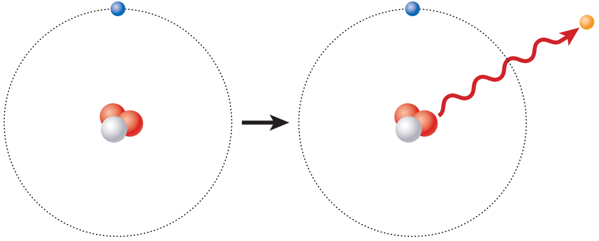
(a)



(b)



(c)



32. Write the nuclear reaction equation for each of the following beta decay transformations and state the new element of the daughter atom. Use the periodic table to determine atomic numbers. (7.2) K/U C
    (a) Gold-198 undergoes beta-negative decay.
    (b) Iron-53 undergoes beta-positive decay.
    (c) Argon-37 undergoes electron capture.

33. (a) When does gamma decay occur and what particles are emitted or absorbed?
    (b) How does this type of decay affect the structure of the atom? Is it a transmutation?
    (c) What is the general equation for gamma decay? (7.2) K/U

34. Use the knowledge you have gained about radiation and decay to identify the nuclear reaction involved for each of the following equations. State how you can determine this. (7.2) T/I
    (a) ${}^{232}_{90}\text{Th} \rightarrow {}^{228}_{88}\text{Ra} + {}^{4}_{2}\text{He}$
    (b) ${}^{26}_{13}\text{Al} + {}^{0}_{-1}\text{e} \rightarrow {}^{27}_{12}\text{Mg}$
    (c) ${}^{85}_{36}\text{Kr} \rightarrow {}^{84}_{37}\text{Rb} + {}^{0}_{-1}\text{e}$
    (d) ${}^{19}_{10}\text{Ne} \rightarrow {}^{20}_{9}\text{F} + {}^{0}_{+1}\text{e}$

35. (a) Potassium-42 decays into calcium-42 with a half-life of 12.4 h. Suppose you are given a sample of potassium-42 that has an initial mass of 512 mg. Copy and complete **Table 1**.

Table 1

Time (h)	Mass of potassium-42 (mg)	Mass of calcium-42 (mg)	Total mass (mg)
0			
12.4			
24.8			
37.2			

    (b) What scientific law is demonstrated by the numbers in the last column? (7.3) K/U

36. (a) Nitrogen-16 has a half-life of 7.2 s. How much of a 320 mg sample will remain after 11 s?
    (b) Iron-53 has a half-life of 8.51 min. After 15.0 min, 132 mg remain from the original sample. What was the initial mass of the iron-53 sample? (7.3) T/I

37. Calculate the mass defect (in atomic mass units) and the binding energy (in mega-electron volts) of the nucleus of each element. (7.4) T/I
    (a) beryllium-9, which has an atomic mass of 9.01218 u
    (b) oxygen-16, which has an atomic mass of 15.9994 u

38. (a) What does the term *mass–energy equivalence* mean?
    (b) What does the term *mass defect* mean?
    (c) How do the terms in (a) and (b) relate to each other? (7.4) K/U

39. In your own words, explain the process of nuclear fission that is used in nuclear reactors. Include how a chain reaction works, the meaning of critical mass, and how these reactions are maintained. (7.4) K/U C

40. CANDU reactors provide Ontario with over 50 % of its energy while maintaining a strong safety record. (7.4) K/U
   (a) State another term for the core of a nuclear reactor. What is contained in the core and what activity occurs in the core?
   (b) Describe how thermal energy from the fission reactor is transferred into electricity.
   (c) What devices are used to control the reaction rate of the nuclear fuel? What safety features do these devices have in case of an electrical malfunction to the power reactor?
   (d) What other safety features are used in nuclear power plants to protect the people that work on site? What happens to the nuclear waste?

41. (a) Nuclear fusion works in the opposite way of nuclear fission by combining smaller elements to create heavier ones. If fission reactions give off energy, do fusion reactions absorb energy? Discuss this statement, and in your own words explain how it is still possible to get energy out of a fusion reaction.
   (b) Which process produces more energy, fusion or fission? How does this depend on the mass of the reactants that are used? (7.5) K/U C

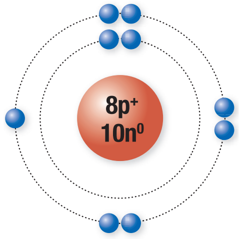
42. (a) What is the most common source of energy that is created by nuclear fusion and why is it difficult to create controlled fusion in a lab?
   (b) Are there any promising advances for creating a nuclear fusion reactor? If so, how do they work and why have they not been implemented on a large scale yet? (7.5) K/U C

43. In this chapter, you learned about many of the different applications of nuclear technology. One of the more controversial applications is the replacement of chemical pesticides with nuclear radiation to help control harmful insects and other nuisance organisms. Describe how nuclear technology is used for this and the issues involved with its widespread use. (7.6) K/U C

Analysis and Application

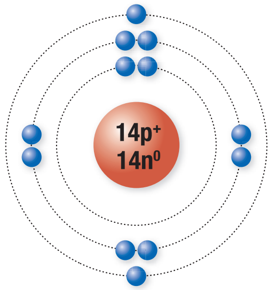
44. The following Bohr–Rutherford diagrams contain at least one mistake. Use the given name of the element, the periodic table, and the knowledge gained in this chapter to identify the mistakes and draw the correct diagram. Each atom should be considered to be in its ground state. (7.1) T/I C

(a)



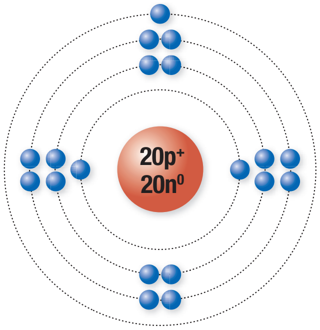
fluorine-19

(b)



silicon-28

(c)



calcium-44

45. (a) In your own words, describe what happens when an atom undergoes alpha decay. What is an alpha particle, and how are the mass and atomic numbers changed?
   (b) Determine the element that is produced when thorium-232 undergoes alpha decay, and write the reaction equation.
   (c) Using your knowledge of the strong force, the electrostatic force, and how an atom changes when it undergoes alpha decay, explain why alpha decay occurs. What are typical characteristics of an element that undergoes alpha decay? (7.2) T/I C

46. (a) Explain, in your own words, the process of beta negative decay. What is the beta particle in this situation? What happens to the atomic and mass numbers? Use the knowledge you have gained in this chapter about the strong and electrostatic forces and nuclear stability to explain why a particular isotope would undergo beta negative decay. What are the common characteristics of an isotope that undergoes beta negative decay?
    (b) Explain, in your own words, the process of beta positive decay. What is the beta particle for this situation? What happens to the atomic and mass numbers? Use the knowledge you have gained in this chapter about the strong and electrostatic forces and nuclear stability to predict why a particular isotope would undergo beta positive decay. What are the common characteristics of an isotope that undergoes beta positive decay?
    (c) Describe the process of electron capture and why it is considered a form of beta decay. What is the beta particle for this situation? What happens to the atomic and mass numbers? Use the knowledge you have gained in this chapter about the strong and electrostatic forces and nuclear stability to predict why a particular isotope would undergo electron capture. What are the common characteristics of an isotope that undergoes electron capture?
    (d) For each isotope state the type(s) of decay (alpha, beta negative, beta positive, or electron capture) that would most likely occur and give reasons to support your answer. (7.2) T/I C
        (i) $^{32}_{15}\text{P}$
        (ii) $^{19}_{10}\text{Ne}$
        (iii) $^{131}_{53}\text{I}$
        (iv) $^{238}_{92}\text{U}$

47. (a) Use what you have learned in this chapter to determine what is wrong with the following nuclear equation: $^{235}_{92}\text{U} \rightarrow {}^{142}_{56}\text{Ba} + {}^{91}_{36}\text{Kr} + 3^{1}_{0}\text{n}$
    (b) After determining the correct equation, calculate the amount of energy given off in this fission reaction. The mass of barium-142 is 141.916 u, the mass of krypton-91 is 90.923 u, and the mass of uranium-235 is 235.044 u. (7.4, 7.5) T/I

48. For the proton-proton chain equation given in the chapter, determine the amount of energy that is given off. Refer to Appendix B to determine the mass of any unknown elements. (7.5) T/I A

Evaluation

49. Of the types of radiation that you learned about in this chapter, which emitted particles can penetrate the furthest? List the different types of emitted particles and predict why each can penetrate as far as it does. T/I

50. Knowing the half-life of isotopes has led to a larger understanding of radioactivity and the development of new technology. Suppose that you are given a sample of an isotope with a known mass. How would you design an experiment to determine the half-life? What could you do to ensure accurate measurements in case the half-life is incredibly long? What if the half-life is incredibly short? (7.3) T/I

51. (a) Nuclear technology has created enormous potential for creating an abundant energy source with very little fuel and for some countries has replaced coal as the leading source of energy. Do you think that one day this technology may be used in other areas such as transportation? Would it be possible to use this technology for cars or airplanes? Why or why not? Are there any vehicles today that use nuclear reactors?
    (b) Do you think that one day we may use a form of this technology for space travel and replace the bulky fuel tanks we currently use? Why or why not? Think of Newton's laws and what would be needed to move an object through space. (7.4) T/I C

Reflect on Your Learning

52. (a) Use a concept map to summarize the basic vocabulary and concepts surrounding nuclear reactions and nuclear technology covered in this chapter.
    (b) Write a short essay using these terms. In your essay, describe how stars get their energy by explaining how a nuclear reaction works. C

53. Create a two-column table. In the left column, outline your perception of nuclear technology before reading this chapter. Include perceptions about mutations that Hollywood portrays in its science-fiction movies. In the right column, outline which perceptions changed and what new information you have learned about nuclear technology. C

Research

GO TO NELSON SCIENCE

54. One of the most important people to pioneer the way for physicists in understanding the atom was Marie Curie (**Figure 1**). Use the Internet and other sources to research her contributions to this field of science and write a paper on your findings. What achievements did she attain? What was the cause of her death? C A

Figure 1

55. With over 50 % of Ontario's power being generated by nuclear energy, the issue of what to do with the waste is hard to ignore. Use the Internet and other sources to research nuclear waste. Write a few paragraphs about how much nuclear waste Ontario produces compared to other countries and how this waste is managed. What safety devices are used in the storage sites and how long do the waste containers need to remain there? C A

56. Most people would deny owning a household device that uses nuclear radiation technology. Some might falsely guess that their microwave uses nuclear radiation technology. Smoke detectors, however, are one of the most common applications of nuclear technology (**Figure 2**). Use the Internet and other sources to research smoke detectors. In a few paragraphs, describe how this technology works. What element is commonly used, how much, and what is its half-life? Are there any health threats from this radiation? K/U C A

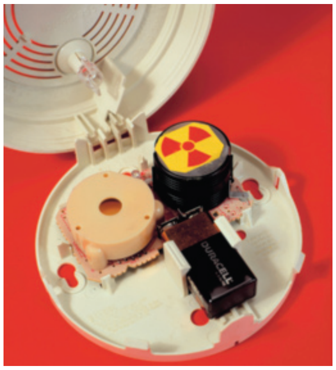


Figure 2

57. Many people do not know that indoor air pollution can be as much as ten times as great as outdoor pollution. Since many homes are highly insulated to preserve energy, they also have poor ventilation, which can cause the pollutants in the air to remain for years. Because of this, one of the growing concerns in the past couple of decades is the increase in radioactive radon gas, which can lead to lung cancer from overexposure. Use the Internet and other sources to research this topic. Discuss the causes of this pollution and what measures can be taken to help keep people safe. K/U C A

58. Although magnetic confinement has been promising in leading us to a possible method of nuclear fusion, other methods have had some recent breakthroughs as well. Use the Internet and other sources to research the topic of inertial confinement fusion and write a paper discussing the methodologies used to create nuclear fusion. Also include any information you find about any recent breakthroughs this technology has had and any plans that countries might have to further research this technology. C A

59. Perhaps the most abundant source of radiation that is not mentioned in this chapter is the neutrino. Research this particle and write a few paragraphs that answer the following questions: T/I C A
    (a) Where do neutrinos come from?
    (b) How many are produced each second?
    (c) How far can they permeate into a piece of lead?
    (d) Is there any danger or health risk from this radiation?

60. In this chapter, you learned that sometimes certain isotopes of atoms will undergo beta positive decay where a positron is ejected. A positron is the same as an electron except that it has a positive charge. In particle physics, these are known as anti-particles or anti-matter. Perform research to answer the following questions: T/I C A
    (a) What are the anti-particles of the other known particles discussed in this chapter?
    (b) Why is there little anti-matter in the universe?
    (c) What happens when a particle and its anti-particle meet?
    (d) Using Einstein's equation, do a quick calculation to determine how much energy would be given off when a hydrogen nucleus and an anti-hydrogen nucleus meet.

My School's Sustainable Energy Plan

Public buildings such as schools and hospitals use large amounts of energy. While most of the energy is used for heating and cooling, some is also used for lighting and communication. In addition to furnaces and air conditioners, schools and hospitals use telephones, photocopiers, refrigerators, and computers. As the cost of energy increases, governments study ways to reduce their energy costs and their contribution to environmental pollution.

Schools, in particular, should try to save energy for educational, economic, and environmental reasons. Schools should do their best to use energy wisely to set a good example for their students. Schools are used primarily during school hours from Monday to Friday and only during the school year, September to June. Thus, the use of energy-consuming devices should be regulated according to these periods of time. In addition, schools should do their best to use the most environmentally friendly and energy-efficient systems possible.

Father Michael McGivney Secondary School in Markham, Ontario, is an example of a large high school (area = 16 500 m^2) that installed a series of air–air heat pumps in the ceiling spaces above corridors and geothermal heat pumps in the school's boiler rooms. The thermal energy obtained from these sources provides hot water for general use and hot air for the school's forced-air heating system. The heat pump system at Father McGivney Secondary School cost approximately $120 000 more than a conventional natural gas heating system to purchase and install, but the system saves the school about $9500 per year in energy costs. Thus, the additional purchase and installation costs have been recovered in just over 12 years. Regulating the use of other energy-using devices, such as lights, computers, and photocopiers, may help the school save even more money and create even less environmental pollution.

The Issue

You will investigate the energy-transforming systems of a school and, using what you have learned about energy and society, recommend changes that may increase sustainability, reduce financial costs, and reduce environmental pollution.

ROLE

A group of four to six students will form a Sustainable Energy Commission whose task it is to advise the rest of the class and possibly the school's administration and/or school board of changes that the school can implement to make the school more energy efficient and energy sustainable. The rest of the class will be divided into three or four student committees that focus on different academic departments within the school. For example, the Physical Education Committee will investigate the energy systems in the physical education department and the Science Committee will investigate energy use in the science department.

Three other committees will be formed: a Common Areas Committee, an Administration Committee, and a Utilities Committee. The Common Areas Committee will study the common areas of the school, including hallways and cafeterias; the Administration Committee will analyze office areas such as the school's main office, guidance office, and staff lounges; and the Utilities Committee will study the school's utility areas containing the school's central heating and cooling systems.

Committees will investigate structures such as windows and doors and energy-transforming devices such as computers, refrigerators, and heating and cooling systems. Each committee will study a department's energy needs and uses and make recommendations about how the department may regulate energy use; reduce energy consumption; and consider the purchase, installation, and use of more energy-efficient systems and devices.

AUDIENCE

Department Committees will present their findings and recommendations to the Sustainable Energy Commission. The Sustainable Energy Commission will present its findings to the whole class and possibly to the school and school board administration.

Goal

To research and suggest strategies the school may use to reduce the financial costs of the energy-transforming systems within the school, increase energy sustainability, and reduce the school's contribution to environmental pollution

Research and Identify Solutions

Conduct an internal audit of the energy-transforming systems used in the various departments of a school. Conduct Internet or library research to identify more efficient energy systems and devices that may be used to replace the less efficient systems currently being used in the school.

GO TO NELSON SCIENCE

Make a Decision

Apply what you have learned about efficiency and energy use in this unit to evaluate which energy-transforming systems currently being used in the school may be replaced with more efficient systems. Calculate how much the school's efficiency could be improved by a new system. Finalize your recommendation with your committee.

Communicate

Department Committees will present their findings to the class's Sustainable Energy Commission in the form of a written report and audiovisual presentation involving a variety of multimedia tools and strategies, including posters, pamphlets, video recordings, audio recordings, interactive whiteboards, and presentation software. Your presentation should include how you calculated the percent improvement in efficiency the new systems would achieve.

ASSESSMENT **CHECKLIST**

Your completed Unit Task will be assessed according to these criteria:

Knowledge/Understanding

- ✓ Demonstrate knowledge of renewable and non-renewable energy resources.
- ✓ Demonstrate knowledge of energy transformations, efficiency, and power.
- ✓ Demonstrate knowledge of technologies that apply principles of and concepts related to energy transformations.
- ✓ Describe the impact of heating and cooling systems on society and the environment.
- ✓ Describe social and environmental issues related to energy.

Thinking/Investigation

- ✓ Conduct an internal audit of the school's energy-transforming systems.
- ✓ Research strategies that could reduce the financial cost of energy-transforming systems.
- ✓ Evaluate various solutions for reducing energy-related costs.
- ✓ Compare the efficiency of various systems.

Communication

- ✓ Synthesize findings in the form of a written report.
- ✓ Communicate findings in audiovisual format using a variety of multimedia tools.
- ✓ Communicate recommendations clearly and concisely.

Application

- ✓ Apply knowledge to an unfamiliar context.
- ✓ Propose a course of practical action.
- ✓ Justify recommendations using research.

UNIT 3 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. A man pulls his luggage on a 30.0° incline with a constant force of 25 N. How much work does he do after walking 20.0 m? (5.1) T/I
   (a) 1500 J
   (b) 250 J
   (c) 430 J
   (d) 330 J
2. The type of energy possessed by moving objects is
   (a) kinetic energy
   (b) potential energy
   (c) chemical energy
   (d) work energy (5.2) K/U
3. What is the kinetic energy of a 25 kg object moving at 5.0 m/s? (5.2) T/I
   (a) 120 J
   (b) 63 J
   (c) 620 J
   (d) 310 J
4. According to the law of conservation of energy, which of the following is true? (5.3) K/U
   (a) Since the Big Bang the amount of energy in the universe has been increasing.
   (b) Energy only disappears during nuclear reactions.
   (c) When an energy transformation occurs, no energy is lost.
   (d) Energy can be created out of space.
5. To transfer input energy into kinetic energy, which of the following devices is most efficient? (5.4) K/U
   (a) electric car
   (b) bicycle
   (c) gas vehicle
   (d) animal muscles
6. What power input is needed for a 70.0 kg person to go up 5.00 m of stairs in 2.00 s? (5.5) T/I
   (a) 3430 J
   (b) 175 J
   (c) 1720 J
   (d) 340 J
7. An increase in the motion of the particles that make up a substance will have what effect? (6.1) K/U
   (a) It will make the substance warmer.
   (b) It will make the substance colder.
   (c) It will make the substance spin.
   (d) It will not have any effect on the substance.
8. The term used to describe the transfer of thermal energy that occurs when warmer objects are in physical contact with colder objects is
   (a) thermal convection
   (b) thermal induction
   (c) thermal radiation
   (d) thermal conduction (6.2) K/U
9. The specific heat capacity of a substance measures which of the following? (6.3) K/U
   (a) the amount of energy required to raise the temperature of 1 L of the substance by 1 °C
   (b) the amount of energy required to change the state of matter of the substance from liquid to gas
   (c) the amount of energy required to raise the temperature of 1 kg of the substance by 1 °C
   (d) the amount of energy required to bring the substance into a plasma state
10. The amount of energy released or absorbed by a substance during a phase transition is called
    (a) latent heat
    (b) specific heat
    (c) phase heat
    (d) transition heat (6.4) K/U
11. Which of the following systems uses thermal energy from Earth for heating and cooling? (6.5) K/U
    (a) electrical heating systems
    (b) geothermal systems
    (c) forced-air system
    (d) hot water heating system
12. Which particle can only occupy certain energy levels and circles the nucleus of an atom? (7.1) K/U
    (a) proton
    (b) neutron
    (c) electron
    (d) positron
13. How does the atomic number of an element change when it undergoes alpha decay? (7.2) K/U
    (a) increases by 1
    (b) decreases by 1
    (c) increases by 2
    (d) decreases by 2
14. If a substance has a half-life of 3.00 h, how much of a 512 mg sample will remain in 5.00 h? (7.3) T/I
    (a) 144 mg
    (b) 161 mg
    (c) 212 mg
    (d) 256 mg

15. How does the mass of the nucleus of an atom compare to the sum of the masses of its individual particles? (7.4) K/U
    (a) The mass of the nucleus is smaller than the sum of the masses of the individual particles.
    (b) The mass of the nucleus is larger than the sum of the masses of the individual particles.
    (c) The mass of the nucleus is the same as the sum of the masses of the individual particles.
    (d) The particles in the nucleus do not exist in free form.
16. Which of the following is used to cool Canada's CANDU reactors? (7.4) K/U
    (a) regular water
    (b) salt water
    (c) light water
    (d) heavy water
17. The process of getting energy by combining two small nucleons to form a larger one is known as
    (a) nuclear fission
    (b) nuclear fusion
    (c) nuclear reaction
    (d) nuclear bombardment (7.5) K/U

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

18. A force that acts in a direction perpendicular to the motion of an object does positive work on the object. (5.1) K/U
19. The kinetic energy of an object can be determined by multiplying the mass by the square of the velocity of an object. (5.2) K/U C
20. Gravitational potential energy is equal to the mass of an object times the acceleration of gravity times the height above a given reference point. (5.2) K/U
21. A person who jumps into a pool will hit the water with the same amount of kinetic energy as the amount of potential energy they had from the height they jumped. (5.3) K/U
22. A hydroelectric power plant is about twice as efficient at producing electrical energy as a nuclear power plant. (5.4) K/U
23. Power is equal to the amount of mechanical work done divided by the distance over which the work was performed. (5.5) K/U
24. Temperature is a measure of the average kinetic energy of the particles in a substance. (6.1) K/U
25. The Fahrenheit scale is based on the total amount of thermal energy that a substance possesses. (6.1) K/U
26. Two objects that are made out of the same substance and have the same mass will also have the same amount of thermal energy when they are at the same temperature. (6.2) K/U
27. Heat is a term used in science to describe the transfer of thermal energy from a colder object to a warmer one. (6.2) K/U
28. The specific heat of water is 2.18×10^3 J/(kg•°C). (6.3) K/U
29. The increase in volume of a substance due to an increase in temperature is known as thermal expansion. (6.3) K/U
30. The specific latent heat of a substance is the amount of thermal energy required for 1 kg of a substance to change from one state into another. (6.4) K/U
31. When an atom is in its normal state, the number of protons is usually greater than the number of electrons. (7.1) K/U
32. The second shell of an atom can hold 18 electrons. (7.1) K/U
33. Different isotopes of the same element contain the same number of protons but a different number of neutrons. (7.1) K/U
34. During beta positive decay, the nucleus of the atom emits an electron. (7.2) K/U
35. The half-life of carbon-14 and the amount known in our environment can be used to determine the age of fossils. (7.3) K/U
36. Per gram of material, nuclear fission produces more energy than nuclear fusion. (7.4, 7.5) K/U

Knowledge

For each question, select the best answer from the four alternatives.

1. Several forces are acting on a wooden block, when you apply an additional force. The work you do on the block will be negative if
   (a) the object does not move
   (b) the force you exert and the displacement have the same direction
   (c) the force you exert and the displacement have opposite directions
   (d) the object speeds up (5.1) K/U
2. The forces acting on a car driven on a hilly road do positive work on the car whenever the car is
   (a) coasting uphill
   (b) slowing down
   (c) speeding up
   (d) changing direction (5.1) K/U
3. Which of these is true about the energy of a hockey puck while sliding on a smooth horizontal surface? (5.2) K/U
   (a) Its kinetic energy is always positive.
   (b) Its potential energy continually decreases.
   (c) Its thermal energy decreases as it moves.
   (d) Its total energy increases.
4. Which of these is a statement of the work–energy principle when a single force acts on an object to change its motion? (5.2) K/U
   (a) The change in kinetic energy of the object is equal to its change in potential energy.
   (b) The work done on the object equals its change in kinetic energy.
   (c) There are no changes in energy.
   (d) The object's gravitational potential energy is zero at the reference level.
5. A grocery store customer accidentally lets go of a shopping cart filled with groceries at the top of a ramp. There is significant friction in the wheel bearings of the cart. Which of these remains constant as the cart rolls down the ramp? (5.3) K/U
   (a) kinetic energy
   (b) gravitational potential energy
   (c) mechanical energy
   (d) mechanical energy plus thermal energy
6. In physics, power directly measures
   (a) the magnitude of an exerted force
   (b) the effect of a force in causing acceleration
   (c) the range over which energy is transmitted
   (d) the rate at which energy is transformed (5.5) K/U
7. Which of the following renewable energy resource technologies produces the most electrical energy worldwide? (5.4) K/U
   (a) hydroelectric power plants
   (b) photovoltaic cells
   (c) wind mills
   (d) tidal turbines
8. The kinetic molecular theory explains
   (a) the behaviour of moving electrons in atoms and molecules
   (b) thermal properties in terms of motions of atoms and molecules
   (c) the kinetic energy of everyday objects
   (d) kinetic and potential energy in falling objects (6.1) K/U
9. The thermal energy of any object is
   (a) the total kinetic energy of its particles
   (b) the total potential energy of its particles
   (c) the total mechanical energy of its particles
   (d) the gravitational and kinetic energy of its particles (6.2) K/U
10. Which of these is greater for a cup of boiling water than for an icy lake? (6.2) K/U
    (a) its thermal energy
    (b) its average kinetic energy per molecule
    (c) its boiling point
    (d) its freezing point
11. The direction in which heat transfers between two objects placed in contact is determined by which one has the greater
    (a) thermal energy
    (b) temperature
    (c) contact area
    (d) chemical energy (6.2) K/U
12. When you stand beside a charcoal grill at a picnic, you may feel its warmth even though heated air from the burning charcoal does not reach you. This is an example of heat transfer by
    (a) radiation
    (b) conduction
    (c) convection
    (d) diffusion (6.2) K/U

13. Placing a pot of water on the heating element of an electric stove results in currents of circulating water that distribute the added thermal energy. What drives the current? (6.2) K/U
    (a) Heat rises.
    (b) The small bubbles from dissolved gases make the water circulate before it boils.
    (c) The thermal energy exerts force on the water.
    (d) The colder water away from the heat source is denser, so it sinks and pushes warmer water up.
14. All isotopes of any one chemical element have the same
    (a) number of neutrons
    (b) number of protons
    (c) atomic mass
    (d) half-life (7.1) K/U
15. Which kind of nuclear decay process emits a positron? (7.2) K/U
    (a) gamma decay
    (b) alpha decay
    (c) beta decay
    (d) electron capture
16. Which kind of nuclear decay process emits the most strongly penetrating form of ionizing radiation? (7.2) K/U
    (a) alpha decay
    (b) beta positive decay
    (c) beta negative decay
    (d) gamma decay
17. Can an atomic nucleus emit an electron? (7.2) K/U
    (a) No. The nucleus contains only protons and neutrons.
    (b) No. Producing negative charge from positive charge violates the laws of physics.
    (c) Yes. A neutron in the nucleus can become a proton plus an electron.
    (d) Yes. A proton in the nucleus can become an electron plus a neutron.
18. Carbon dating is a technique that can be used to determine the age of
    (a) any artifact found
    (b) organisms previously alive
    (c) rocks and soil
    (d) the universe (7.3) K/U

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

19. The kinetic energy of a moving object is proportional to the square of its speed. (5.2) K/U
20. According to the work–energy principle, the work done on an object to accelerate it in the absence of friction-like forces equals the change in its potential energy. (5.2) K/U
21. As a roller coaster coasts downhill, its gravitational potential energy is converted into chemical energy and thermal energy. (5.3) K/U
22. The mechanical energy is the sum of the kinetic energy and the electrical energy. (5.3) K/U
23. Hydroelectricity is a renewable energy resource. (5.4) K/U
24. Incandescent light bulbs are less efficient than fluorescent light bulbs because they transform a smaller fraction of electrical energy to thermal energy. (5.4) K/U
25. Thermal energy is a measure of the average kinetic energy of the particles in an object. (6.1) K/U
26. Most substances contract as they freeze. (6.3) K/U
27. Substances absorb energy while boiling. (6.3) K/U
28. The latent heat of fusion of a substance measures the energy it absorbs while freezing. (6.3) K/U
29. The behaviour of water as it is cooled below 4 °C results from the way an oxygen atom in each molecule attaches itself to a hydrogen atom in a neighbouring molecule. (6.3) K/U
30. Alpha decay is a process in which an atomic nucleus emits a helium nucleus. (7.2) K/U
31. The repulsive electrostatic force between protons gets weaker as the protons are brought closer together. (7.2) K/U
32. Gravity is the fundamental force primarily responsible for holding nuclei together despite the electrical repulsion between positively charged protons. (7.2) K/U

Match each type of medium on the left with the most appropriate type of energy on the right.

33. (a) stretched spring (i) electrical energy
    (b) flashlight battery (ii) kinetic energy
    (c) visible light (iii) chemical energy
    (d) moving object (iv) elastic energy
    (e) electric current (v) radiant energy (5.3) K/U

Understanding

34. A smooth 0.165 kg hockey puck slides along a smooth floor at an initial speed of 1.0 m/s, and stops in a distance of 2.26 m. (5.1) T/I
    (a) Calculate the work done by the normal force that the floor exerts upward on the puck.
    (b) Calculate the work done by friction.

35. The graph in **Figure 1** shows the force *F* acting on an object to move it along a straight-line path. (5.1) T/I C

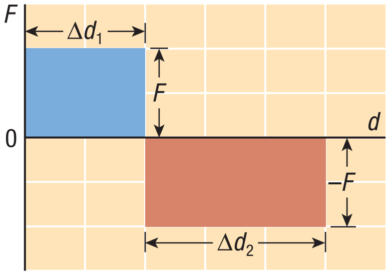


Figure 1

    (a) During which part of the motion are the force and the velocity in the same direction?
    (b) What is the total work done on the object by the force?

36. A 0.145 kg baseball has a kinetic energy of 74 J. Find its speed. (5.2) T/I

37. Explain the role of a reference level in problems involving gravitational potential energy. (5.2) K/U C

38. Suppose a rock is thrown directly upward on the Moon, where air resistance is zero. (5.3) K/U C
    (a) Describe how the work done by the Moon's gravity affects the kinetic energy and velocity of the rock as it moves directly upward.
    (b) How do the potential energy and the mechanical energy of the rock change on its way upward from the Moon's surface?
    (c) How are the kinetic energy and the potential energy each affected by the work that gravity does on the rock as it next falls downward?

39. A student throws a 0.22 kg rock horizontally at 20.0 m/s from 10.0 m above the ground. Ignore air resistance. (5.3) T/I
    (a) Find the initial kinetic energy of the rock.
    (b) Find the kinetic energy of the rock as it strikes the ground.
    (c) Find the speed of the rock as it strikes the ground.

40. A roller coaster starts at rest from a height of 110 m, and accelerates down the track to a height of 10.0 m. Find the speed it can reach, assuming no friction. (5.3) T/I

41. Explain why a device with efficiency greater than 100 % would violate the laws of physics, and why even 100 % efficiency never occurs for any energy-transforming device. (5.4) K/U C

42. A 0.057 kg tennis ball is dropped from 1.22 m onto a hard surface, bouncing up to a height of 0.70 m. (5.4) T/I
    (a) What was the kinetic energy of the ball just before it hit the ground for the first time?
    (b) How much kinetic energy did the ball have just after it hit the ground for the first time?
    (c) What happened to the lost energy?
    (d) What was the percent efficiency of the ball bouncing off the ground?

43. A farmer is considering putting in a wind turbine on his property to produce electricity. After doing some research, he comes up with the following two graphs (**Figure 2** and **Figure 3**): (5.5) K/U C A

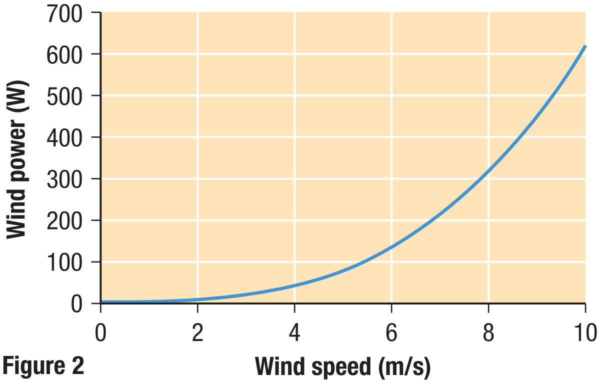


Figure 2

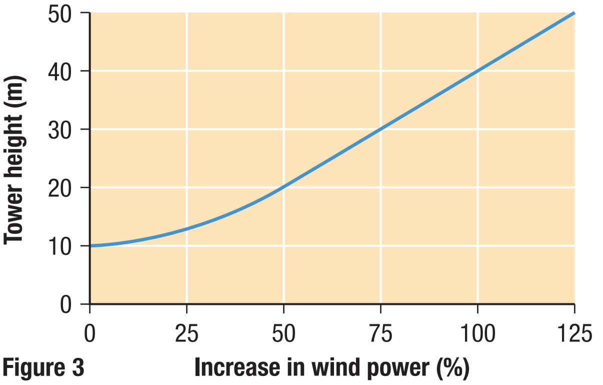


Figure 3

    (a) Describe what happens to wind power as wind speed increases.
    (b) Describe what happens to wind power as the height of the tower for the wind turbine increases. Why do you think this happens?
    (c) If the average wind speed on the farm is not very high, what can the farmer do to increase power generation? How will this affect the construction cost? Explain your reasoning.

44. A 100.0 W incandescent light bulb emits about 1.6 J of energy as useful, visible light each second. What is its efficiency? (5.4) T/I

45. A force of 110 N is applied horizontally to the handles of a lawnmower to move it at a speed of 0.80 m/s across a lawn. Find the power used to mow the lawn. (5.5) T/I

46. A motor that uses electrical energy at a rate of 1.5 kW is connected to a hydraulic lift that is used to lift a 1300 kg car to a height of 1.8 m in 24 s at constant speed. Find the efficiency of the system consisting of the motor and the lift. (5.5) T/I

47. A certain 100 W light bulb has an efficiency of 95 %. How much thermal energy will this light bulb add to the inside of a room in 2.5 h if the bulb is on for the whole time? (5.5) T/I

48. Explain how heat differs from thermal energy. (6.1) K/U

49. (a) Express −20 °C as a temperature on the Kelvin scale.
    (b) Express 68 K as a Celsius temperature. (6.1) K/U

50. Use the temperature difference between the boiling and freezing points of water on each scale to determine how many Fahrenheit degrees of change in temperature are equal to each Celsius degree change in temperature. (6.1) T/I

51. List and describe each of the three main mechanisms for heat transfer. (6.2) K/U C

52. Explain the purpose served by the air space and by the shiny reflecting surfaces in the Thermos bottle shown in **Figure 4**. What kind of heat transfer does each feature reduce? (6.2) C A

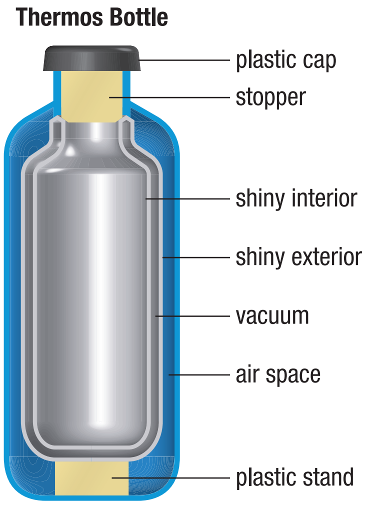


Figure 4

53. When you touch a metal spoon at room temperature it will usually feel colder than when you touch a woollen blanket at the same temperature. Explain what causes this effect. (6.2) K/U C A

54. A 170.0 g sample of a substance is heated to 120.0 °C and then plunged into 200.0 mL of water at 10.0 °C. The resulting mixture has a temperature of 12.6 °C. What is the specific heat capacity of the substance? (6.3) T/I

55. Find how much thermal energy must be added to 200.0 g of iron to increase its temperature by 12 °C. (6.3) T/I

56. A Canadian penny is initially at 100.0 °C. Estimate how much energy it must lose to cool to room temperature at 20.0 °C. The penny consists of 94 % iron with smaller amounts of nickel and copper and has a total mass of 2.35 g. (6.3) K/U T/I

57. Water at 20.0 °C is mixed with 120.0 g of ethyl alcohol at 10.0 °C in a thermally insulated container. If the final mixture has a temperature of 16.0 °C, how much water was added? (6.3) T/I

58. An ice cube is dropped into a large graduated cylinder. From the change in level of the water already in the cylinder the ice cube is found to have a mass of 20.0 g. Find how much energy the ice cube releases merely by melting. (6.4) T/I

59. The graph in **Figure 5** shows how the temperature varies as the thermal energy of a container full of water is increased at a constant rate. Explain what is happening to the sample for part A, part B, and part C of the curve. (6.4) K/U C

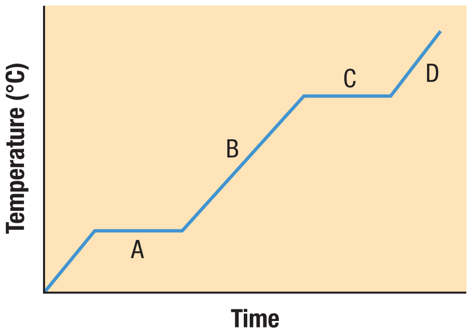


Figure 5

60. Explain what happens to the added thermal energy during a phase transition, when the average kinetic energy of particles in the sample does not increase. (6.4) K/U C

61. Draw the Bohr–Rutherford diagram for sodium-23. (7.1) K/U C

62. Use Bohr–Rutherford models to explain how an excited state differs from the ground state of an atom. (7.1) K/U C

63. What does each of these terms describe in the Bohr–Rutherford atomic model? (7.1) K/U
   (a) atomic mass number
   (b) atomic number
   (c) nucleon

64. Compare the atomic number, atomic mass number, and number of neutrons of $^{99}_{43}\mathrm{Tc}$ and of $^{96}_{43}\mathrm{Tc}$. (7.1) K/U C

65. (a) Which two forces within a nucleus compete to determine how stable a particular nuclear isotope is?
   (b) How can the presence of additional neutrons increase the stability of an isotope in some cases? (7.2) K/U C

66. Calculate the mass defect and binding energy of the iron-56 nucleus with atomic mass 55.934 937 5 u. (7.4) T/I

67. Beryllium-11 has a half-life of 13.81 s. What percent of the initial sample will remain after 30.0 s? (7.3) T/I

68. (a) What is nuclear fission?
   (b) Do nuclei that are fissionable have larger or smaller masses than most nuclei?
   (c) What particle is typically absorbed by the nucleus to induce nuclear fission?
   (d) Why does it require much less energy to induce fission of a fissionable nucleus than to induce nuclear fusion of hydrogen atoms? (7.4) K/U C

69. (a) Explain the role of the control rods in a nuclear reactor, and include an example of a substance used for control rods in CANDU reactors.
   (b) Explain the function of a moderator in a nuclear reactor, and identify a substance used as a moderator in CANDU reactors. (7.4) C A

70. Explain how the binding energy of stable nuclei varies with increasing atomic mass. What does this imply about which isotopes can be combined more readily by fusion and which are more likely to undergo fission? (7.5) K/U C

71. Determine the net energy released in the overall proton-proton chain fusion reaction shown below. Remember to consider the mass defect. (7.5) T/I

$$4(^{1}_{1}\mathrm{H}) \rightarrow {}^{4}_{2}\mathrm{He} + 2(^{\ 0}_{-1}\mathrm{e}) + \text{energy}$$

72. (a) Which of the reactions below is a fusion reaction? Explain how you know.
   (i) $^{204}_{82}\mathrm{Pb} \rightarrow {}^{200}_{80}\mathrm{Mg} + {}^{4}_{2}\mathrm{He}$
   (ii) $^{234}_{90}\mathrm{Th} \rightarrow {}^{234}_{92}\mathrm{Pa} + {}^{\ 0}_{-1}\mathrm{e}$
   (iii) $^{2}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n}$
   (b) Which of the reactions in (a) is beta decay? Explain how you know. (7.5) T/I

Analysis and Application

73. A 62 kg person is riding on an escalator at constant speed to a height of 4.3 m. The escalator makes an angle of 45° with the horizontal. (5.1) T/I
   (a) Draw a free-body diagram of this situation.
   (b) Calculate the work that the escalator does on the passenger.
   (c) Find the work done by gravity.

74. A child pulls a sled along the ice by exerting a force of 40.0 N on a rope that makes an angle of 30.0° with the horizontal. Find how much work the force has done on the sled when it moves horizontally through a distance of 2.0 m. (5.1) T/I

75. The Canadarm2 shown in **Figure 6** is attached to the International Space Station and used to move heavy objects off rockets and onto the Space Station. It is 17.6 m long and can exert forces up to 1000 N. How much work will the Canadarm2 do on an object if it moves the object through a displacement equal to its length using the maximum force it can apply? Assume that the force acts in the same direction as the object's displacement. (5.1) T/I

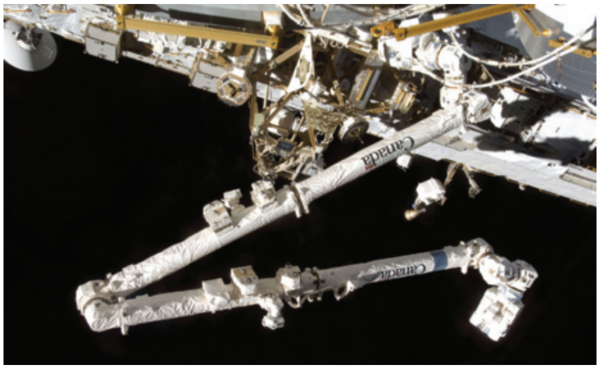


Figure 6

76. Assume a car's brakes when applied produce a constant force to bring the car to a complete stop. Assume the car has mass *M*. Use energy considerations to find out how the stopping distance depends on the initial velocity *v* (for example, is it proportional to *v*, or to v^2, or to $1/v$, and so on). (5.1, 5.2) T/I

77. Suppose you do 200 J of work to compress a spring. (5.2) T/I
   (a) How much work would the spring be able to do when it decompresses, exerting force to move another object?
   (b) How much potential energy is stored in the compressed spring?
   (c) If a 5.0 kg object is placed atop the compressed spring and the spring is released, how high can the spring hurl the object upward?

78. An object hanging from a string like a pendulum is pulled to the side and released, as shown in **Figure 7**. A peg blocks the path of the string. Which letter on the diagram most accurately labels the greatest height that the object could reach during its swing? Justify your answer. (5.3) T/I C

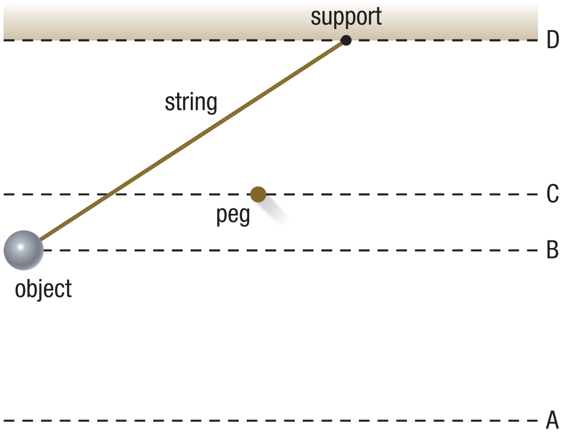


Figure 7

79. Describe which form of energy is transformed into which in a nuclear power plant when
   (a) a nuclear reaction heats water to change it into steam under pressure
   (b) the steam pressure forces a turbine to rotate
   (c) the rotating turbine forces a generator to rotate and produce electricity (5.3) C A

80. Suppose a bicycle and its rider have a mass of 75 kg. The bicyclist does 4700 J of work to travel 210 m along a slightly sloping road that increases the bicyclist's elevation by 5.5 m. Find the efficiency of the bicycle. (5.4) T/I A

81. Find what power is needed to accelerate a 620 kg Formula One car and driver "from zero to sixty" (miles per hour, or mph) in 6.00 s (1 mph = 0.447 m/s). (5.5) T/I

82. On average, 110 000 m^3 of water flow over Niagara Falls each minute and fall through a height of about 52 m. (5.5) T/I
   (a) Calculate the change in gravitational potential energy of the water that flows over Niagara Falls in 1.00 min.
   (b) If all the potential energy lost in going over the falls could be converted to electrical energy, what would the power rating of Niagara Falls be?

83. Two students decide to measure the power rating of a small submersible electric water heater. They place 325 mL of water at 20.0 °C in a thermally insulated container, insert the water heater and a thermometer, and run an electric current through the heater for 60.0 s, stirring the water to keep its temperature uniform. They find that the water reaches 24.9 °C. Calculate the power of the heater in watts. (5.5, 6.3) T/I

84. What are the main ideas in the caloric theory and how did it explain how a hot object would heat a colder object? In what way does Count Rumford's experiment, and simply experiencing what happens when you rub your hands together, show the caloric explanation of warming objects to be inadequate? Explain. (6.1) K/U C

85. The Kelvin temperature scale has a universal meaning related to the thermal energy an object contains. Any object at zero kelvins has the least kinetic energy physically possible for the particles comprising it. Why then would scientists have invented the Celsius scale first, based merely on the boiling and freezing points of one specific substance, water? (6.1) T/I C

86. (a) Explain in terms of what you know about specific heat and about heat transfer by convection why the water in a lake on a warm summer day stays much cooler than the ground. The specific heat of dry soil is about 0.80 kJ/(kg•K).
   (b) On a hot day, near a large body of water, you will likely enjoy a breeze blowing from the water toward and over the ground. The circulating air returns at higher elevation toward the water. Explain the mechanism that produces this circulating current.
   (c) How does the air near a large body of water circulate at night if the water ends up warmer than the land surface? (6.2, 6.3) T/I C A

87. Discuss how the unusual behaviour of water compared to other liquids accounts for the way that lakes freeze first at their surface during winter, and typically remain liquid below. (6.4) C A

88. (a) Describe briefly how the latent heat of condensation and vaporization is used in an air conditioning system.
   (b) Explain what happens to the thermal energy that the refrigerant removes from inside a home, in terms of the law of conservation of energy. (6.4) K/U C A

89. When outside temperatures appear likely to drop just below the freezing point of water, fruit farmers protect their crop by continuously spraying the plants with water. Explain why this would help keep the crop from being damaged. (6.4) T/I C A

90. Calculate how much thermal energy is removed when 50.0 g of ethyl alcohol vaporizes by boiling. (6.4) T/I

91. Different substances expand at different rates with increasing temperature. Explain how this principle is employed in a thermostat that controls the operation of heating and cooling systems. (6.4, 6.5) C A

92. How much thermal energy is required to melt 8.0 g of gold at its melting point? (6.4) T/I

93. Determine whether a kilogram of molten lead can completely boil a kilogram of water by calculating and comparing the heat released by the lead to reach the boiling point of water with the heat absorbed to heat and then boil the water starting at 20.0 °C. The lead starts in liquid form exactly at its melting temperature, 327.5 °C. (6.3, 6.4) T/I

94. (a) How does the source of thermal energy for a geothermal heating system differ from that of a conventional system?
    (b) What advantages does geothermal heating offer? (6.5, 6.6) C A

95. Write a balanced reaction equation for each of the following nuclear decay processes: (7.2) T/I
    (a) Uranium-238 decays by alpha decay.
    (b) Sodium-22 decays by beta positive decay.
    (c) Calcium-41 decays by electron capture.

96. The graph in **Figure 8** shows the decrease in mass of an unknown isotope caused by nuclear decay. (7.3) T/I C
    (a) Determine the half-life of the isotope from the graph.
    (b) Calculate how much of the isotope would remain after 8000 years.

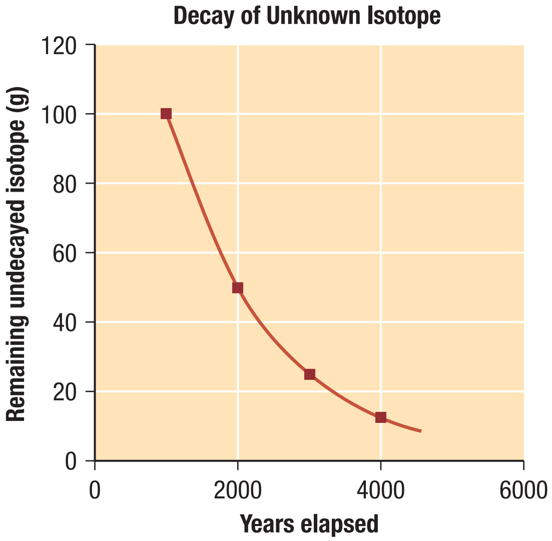


Figure 8

97. A patient comes into the hospital for a bone scan and is injected with a dye containing Tc-99m. The half-life of Tc-99m is 6.03 h. What fraction of the original technetium will remain in the patient 36 h after the procedure if radioactive decay is the only means by which it is removed? (7.3) T/I A

98. When the masses of the correct number of electrons, protons, and neutrons are added together for any particular atomic isotope, the sum never exactly agrees with the measured mass for atoms of the isotope. (7.4) T/I C
    (a) Why is this true?
    (b) How does this difference between the calculated mass and the measured mass of an atomic isotope relate to the interactions between the subatomic particles within the nucleus?

99. Canada's annual consumption of electricity in 2010 has been estimated to be 5.36×10^{11} kWh. If 1.00 kg of matter could be converted completely into electrical energy, how long would it supply Canada's electrical energy needs? (7.4) T/I

Evaluation

100. The Moses-Saunders dam on the St. Lawrence River near Cornwall, Ontario, produces more than 900 000 kW of hydroelectricity. Given what you have learned about the methods of electrical energy production, what advantages does this method have over nuclear and fossil fuel electrical plants? Explain why we cannot use this method exclusively to produce all of Canada's electrical energy. (5.4) T/I C A

101. A group of students are proposing designs for a thermometer to measure only temperatures between 2 °C and 7 °C. One proposal, shown in the diagram in **Figure 9**, would use coloured water instead of coloured alcohol and have a scale from 2 °C to 7 °C. Why is the proposed idea unworkable? (6.3) T/I C A

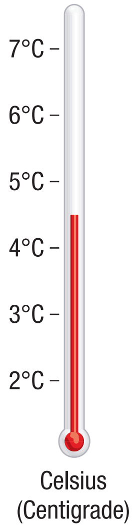


Figure 9

102. An enterprising researcher submits a proposal seeking government funding for a study that would use carbon dating to determine the age of rocks recovered from the moon. Moon rocks generally range in age from 3 billion to 5 billion years old. You are in charge of making decisions about how the government agency's funds are used. (7.3) T/I C A
   (a) Why should you decide not to fund the proposal?
   (b) How might the researcher change the proposal to overcome your objection?

Reflect on Your Learning

103. In your opinion, what is the most important concept you learned in this unit? Why do you feel this is the most important concept? Discuss in a brief paragraph. C

104. The Energy and Society unit covers a broad range of topics. C
   (a) Which topics did you find the most interesting? Explain.
   (b) Which topics did you find easy to understand?
   (c) Which topics did you find the least interesting? Explain.
   (d) Which topics were the most challenging to understand? Explain why and list two things you could do to improve your understanding of these topics.

Research

GO TO NELSON SCIENCE

105. Research the advantages and limitations of passive solar heating. Evaluate whether this would likely provide a cost-effective means of providing the partial or full heating needs of a home in your own location. T/I C A

106. The possibility of laser-induced fusion using "inertial confinement" is a method being explored to create controlled nuclear fusion. Research this method to find out how the process would work, and describe any recent breakthroughs in this field. T/I C A

107. Fuel cells produce electrical energy directly from hydrogen and oxygen. Research the use of hydrogen in energy utilization. Focus on the following issues: T/I C A
   (a) Why is no net energy produced if the hydrogen for the fuel cell is produced by using an electric current to break water apart into hydrogen and oxygen by electrolysis?
   (b) What other means are available to produce hydrogen, and what are their advantages and disadvantages?
   (c) In what ways might hydrogen be useful in energy utilization?

108. Research the average number of kilowatt hours of electricity that a Canadian family uses and estimate, based on your own family's electricity bill and the power rating of electrical lights and electrical devices in your own home, what fraction is for lighting. Use this to estimate how much electrical energy in Canada would be saved each year if all incandescent bulbs were replaced by fluorescent bulbs. T/I C A

109. Deep ocean currents, often referred to as thermohaline currents, take about 1600 years to travel the globe. Research what mechanisms near Earth's poles drive thermohaline currents. Include an explanation of why nearly frozen sea water would sink as it cools, while in freezing lakes the colder water and ice are both at the surface. T/I C A

110. Research radionuclide therapy. How does it work? What are some diseases that can be treated with radionuclide therapy? What are some diseases that cannot be treated using radionuclide therapy at this time? Write a paragraph describing your findings. T/I

111. A number of different isotopes are used in nuclear medicine to image internal organs of the body. Research what properties isotopes must have to be useful for imaging. Consider whether the isotopes should be alpha, beta, or gamma emitters. Consider what the half-lives of the isotopes should be. Discuss why the properties you have identified make these isotopes useful for imaging. T/I C A

UNIT 4

Waves and Sound

OVERALL EXPECTATIONS

- analyze how mechanical waves and sound affect technology, structures, society, and the environment, and assess ways of reducing their negative effects
- investigate, in qualitative and quantitative terms, the properties of mechanical waves and sound, and solve related problems
- demonstrate an understanding of the properties of mechanical waves and sound and of the principles underlying their production, transmission, interaction, and reception

BIG IDEAS

- Mechanical waves have specific characteristics and predictable properties.
- Sound is a mechanical wave.
- Mechanical waves can affect structures, society, and the environment in positive and negative ways.

UNIT TASK **PREVIEW**

For the Waves and Sound Unit Task, you have a choice. You can research a structure or technology mentioned in this unit, or a new technology, and prepare a presentation showing how the properties of waves influence the design or the structure of that choice. Alternatively, you can make a device that demonstrates the concepts about waves and sound learned in this unit.

TSUNAMI OF 2004

On December 26, 2004, movements of Earth off the coast of Sumatra, Indonesia, created a huge disturbance. This disturbance caused a narrow band of ocean floor about 1000 km long to be thrust upward about 15 m in less than 60 s. The enormous pulse of energy set up an extremely large vibration in the Indian Ocean. The vibration crossed thousands of kilometres of open ocean until it reached the shores of Southeast Asia, Sri Lanka, and the eastern coast of Africa and Madagascar. The results were devastating.

The inhabitants of these countries experienced a monster wave called a “tsunami.” Tsunamis are caused by underwater events such as earthquakes and landslides, and they can happen within as little as a minute. The energy pulse from the 2004 tsunami transferred around the world the next day. Many people were amazed that all of this energy could be transported at great speed across such a distance. The destruction of the towns on the shores and the loss of life were monumental. Even though earthquakes, volcanoes, and tsunamis are far more common in that part of the world than in Ontario, few people recognized the signs of the oncoming waves. In one case, however, a 10-year-old girl who had done a school project on tsunamis was able to warn her family of the oncoming wave. As a result, many people near them were able to get to safety.

Energy transfer through waves can be demonstrated by dropping a pebble in the water: once the pebble hits the water, you see waves moving from the source of the disturbance outward. While on a much smaller scale, this phenomenon is similar to the behaviour of the Indian Ocean tsunami. The cause of the tsunami was a rapid uplift of the sea floor, producing significant wave energy that moved away from the uplift. In addition, the uplift was a long line, so the wave that developed was long and more or less straight instead of circular, as with the waves from the pebble. When the source is effectively a straight line, the energy of the wave does not disappear as quickly and can be transported for long distances. The energy that caused this earthquake was so great that in some locations four tsunamis were observed.

An understanding of the physics of waves is important and can be applied in many areas: water waves, music, building construction, airplane safety, oil exploration, and animal communication. You will study all of these applications in this unit.

Questions

1. Many people were completely surprised by the tsunami of 2004. Why do you think people were so surprised?

2. Many people believe that tsunamis are weather related and cannot understand how such a destructive wave can occur on an otherwise sunny day, especially so far from the earthquake. How would you explain such phenomena to these people?

3. Do you think that people should be allowed to live so close to the ocean in areas that are vulnerable to tsunamis, typhoons, and hurricanes? Do you think there should be a government policy about this, or do you think that people should be free to live wherever they please?

UNIT 4 ARE YOU READY?

CONCEPTS

- kinematics terminology
- basic algebra
- kinetic molecular theory
- density
- tension

SKILLS

- observing
- graphing and analyzing data
- researching
- writing
- calculating
- planning
- communicating

Concepts Review

1. Define or explain the following terms: K/U C
    (a) displacement
    (b) speed
    (c) velocity
    (d) acceleration
2. Is tension a force? Explain your answer. K/U
3. Describe the arrangement of the molecules in a gas, such as air. Consider how they are moving as well. K/U
4. Define diffusion as it relates to the dispersion of a gas or vapour. K/U
5. Define temperature, and indicate the relationship between temperature and the motion of gas molecules. K/U
6. Define density. K/U
7. A material has a mass of 75 g and a volume of 30 cm^3. What is its density? T/I
8. Define tension. K/U
9. Study **Figure 1**, and write expressions for the tensions at A, B, and C. Explain your thinking. T/I C

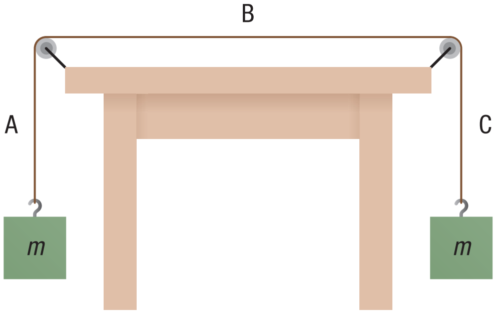


Figure 1

10. In your own words, explain the law of conservation of energy. Use an example in your explanation. K/U C
11. Identify the indicated parts of the wave in **Figure 2**. K/U

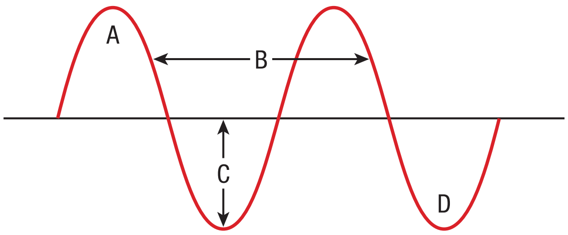


Figure 2

12. Rewrite the following sentence in your own words without using the unit "Hz" or the word "frequency": A wave has a frequency of 20 Hz. C
13. Explain the difference between reflection and refraction. K/U
14. In a graphic organizer, compare the terms "perpendicular" and "parallel." C
15. Copy **Table 1** into your notebook, and supply the missing values. T/I

Table 1 Data for Question 15

Distance (m)	Time (s)	Speed (m/s)
55	35	
1435		85.5
	60	100

16. (a) In general, what do you think is needed to produce sounds?
    (b) Explain how you think sound travels from its source to your ears. K/U
17. (a) Name three sources of loud sounds that you regularly experience in your community.
    (b) Do the loud sounds bother you? Explain your answer.
    (c) Do you think loud sounds are harmful? Why or why not?
    (d) Do you know of anyone who has been harmed by loud sounds? Explain. K/U A

18. Consider the different rooms you have been in and how sound carries in each of them. A
    (a) Are there rooms in which you can easily hear someone speaking from a distance and others in which you can hear the person but not clearly?
    (b) Describe two different rooms and how they are different in their shape or wall coverings.
19. Which do you think travels faster, light or sound? Give two examples and explain with your current knowledge why you believe this to be so. A

Skills Review

20. Given the following equations, isolate the variable c: T/I
    (a) $a + bc = c + da$
    (b) $a^2 = \sqrt{b^2 - 4ac}$
21. Copy **Table 2** into your notebook, and answer the questions below. If you prefer, you can gather your own data by measuring the height and mass of some of your friends. T/I C

Table 2 Data for Question 21

Student	Number of letters in name	Height (m)	Mass (kg)
Susan	5	1.45	51
Yusuf	5	1.73	74
Ying	4	1.52	60
Alexei	6	1.82	87
Sinthu	6	1.56	62
Jake	4	1.70	68
Donna	5	1.60	64

    (a) Using the data in the table, make the following graphs:
        (i) height versus mass
        (ii) height versus number of letters
    (b) Discuss how closely the data appear to be related in (i) and (ii). Do you expect a relationship in both cases?

22. If you were asked to research material on the following subjects, where would you look? Do *not* include general Internet searches. T/I
    (a) examples of solving problems
    (b) examples of physics in our society
    (c) health hazards associated with a given topic in physics
    (d) images relating to physics topics
23. Describe how you would experimentally determine the speed at which sound travels in air outside your school. Include any equations you think would apply. T/I
24. Identify any safety concerns you may have when experimenting with sound. K/U
25. **Figure 3** shows three stringed instruments: a guitar (top), a violin (middle), and a double bass. Which instrument do you think produces (a) the lowest sounds and (b) the highest sounds? Explain your answer. A

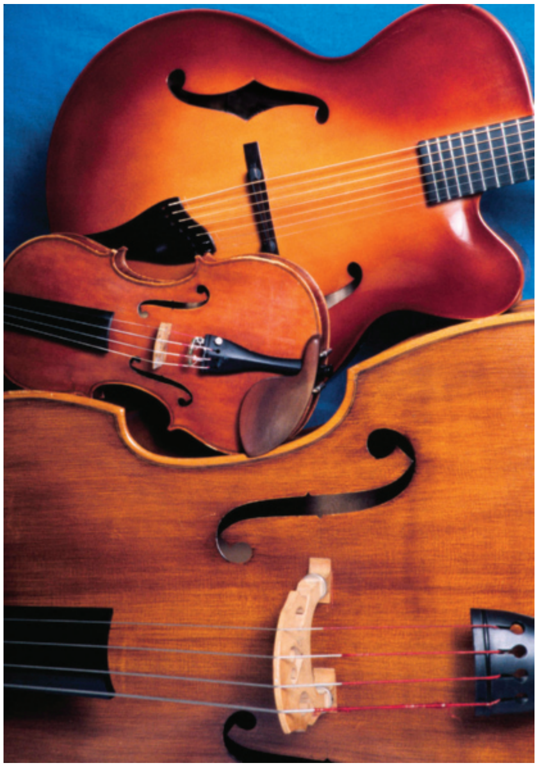


Figure 3

CAREER PATHWAYS PREVIEW

Throughout this unit you will see Career Links in the margins. These links mention careers that are relevant to Waves and Sound. On the Chapter Summary page at the end of each chapter you will find a Career Pathways feature that shows you the educational requirements of the careers. There are also some career-related questions for you to research.

CHAPTER 8

Vibrations and Waves

KEY CONCEPTS

After completing this chapter you will be able to

- understand the nature of vibrations and how they transfer energy
- classify the types of waves and vibrations
- predict particle motion from the type of wave
- draw graphs of the different wave motions
- explore vibrations in one and two dimensions to assess their properties
- analyze the negative impact that sound waves can have on society and the environment
- understand the properties of sound and some applications of sound waves in everyday life

How Do Vibrations and Waves Affect You and the Environment?

We sense vibrations all around us. For example, the beat of a drum, the bouncing of a car as it goes over a bump, and the shaking we feel when we operate a lawn mower are all vibrations. Vibrations can cause disturbances that move away from the source through a material in the form of waves. For example, when you drop a pebble into a pool of water, the disturbance produces water waves, which move away from the point where the pebble entered the water. A leaf floating near the disturbance moves up and down and back and forth about its original position but does not undergo any net displacement as a result of the disturbance. This means that the water wave (or disturbance) moves from one place to another, but the water is not carried with it.

When we observe a water wave, we see a rearrangement of the water's surface. Without the water, there would not be a wave. Similarly, a wave travelling on a string would not exist without the string. Sound waves travel through air as a result of pressure variations from point to point. Therefore, we could consider a wave to be the motion of a disturbance.

Many kinds of waves occur in nature, such as sound waves, water waves, and seismic waves. These very different physical phenomena are described by common terms and concepts introduced in this chapter. In this chapter, you will also learn about the speed of waves, medical applications of sound waves, and how humans first managed to travel faster than sound.

STARTING **POINTS**

Answer the following questions using your current knowledge. You will have a chance to revisit these questions later, applying concepts and skills from the chapter.

1. What is the difference between a vibration and a wave?
2. What do you think happens to the particles of a material when a wave passes through the material?
3. How fast do you think water waves on a lake can travel?
4. What wave terminology do you know? List any terms you know, and explain what each term means.

Mini Investigation

Observing Wave Motion

Skills: Predicting, Performing, Observing, Analyzing, Evaluating, Communicating

SKILLS HANDBOOK **A1.2, A2.1**

In this activity, you will simulate vibrating particles with a wave-like motion moving a Slinky two ways.

Equipment and Materials: Slinky

1. Straighten the Slinky. Lay it out on a large flat surface, such as a desk or a table.
2. Grasp one end of the Slinky and rapidly move it to the left and right (a direction perpendicular to the line of the Slinky). Observe the motion.
3. Return the Slinky to the straightened-out position.
4. Grasping one end, move the Slinky back and forth in the direction of its length (**Figure 1**). Observe the motion.
5. Repeat Steps 2 to 4 but holding the far end of the Slinky.

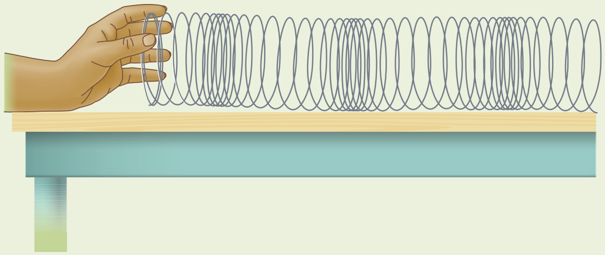


Figure 1

A. Contrast how the Slinky behaved during the two types of motions. T/I C
B. How did the far end behave when it was free? T/I
C. How did the far end behave when it was fixed? T/I

8.1 What Is a Vibration?

In your day-to-day experience you see many objects in back-and-forth motion. For example, the movements of windshield wipers and the pendulum in a clock are back-and-forth motions (**Figure 1(a)**). The wipers and pendulum repeatedly move back and forth along a fixed path, resulting in a cyclical motion. Many of these cyclical motions are more rapid and therefore difficult to see. For example, if you put your hand on the speaker of an operating stereo system, you will feel it shaking with the music. The walls of the speaker are moving back and forth, but they are moving too fast and too slightly to be seen under normal conditions. These objects move back and forth about a middle point, which is called an equilibrium point, or rest position. When the motion stops, the objects return to this point. For instance, if you stop the pendulum in Figure 1(a), it will hang straight down, at the equilibrium point. Notice how the equilibrium point is halfway between the maximum distance that the pendulum swings to the left and to the right. The cyclical motion about an equilibrium point is called a **vibration** (**Figure 1(b)**).

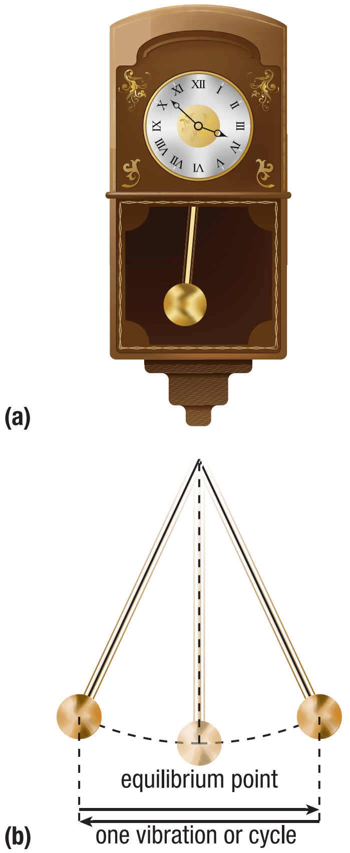


Figure 1 (a) A pendulum's swing has a predictable motion. This predictable motion is used to pace some clocks. (b) One vibration, or one cycle, of the pendulum is one complete vibration.

Vibrations and Mechanical Waves

A pendulum is an isolated object—consider instead particles that are part of a material, like a drumhead. If the particles in the drumhead are disturbed, such as when you beat the drum, the vibrations created by the disturbance are transferred throughout the material. This transfer of energy through a material by particle vibration is called a **mechanical wave**. The material through which a mechanical wave travels is called a **medium**. A medium can be a solid, a liquid, or a gas.

Particle Behaviour in Mechanical Waves

When vibrating, the medium tends to gain or lose very little energy. Thus, a vibration can continue for a long time in some media. A vibration is able to travel through a medium because each molecule in the medium is connected to neighbouring molecules by intermolecular forces. These forces allow the distances between atoms to increase slightly without losing energy. This molecular property of a medium allows a mechanical wave to be one of the most efficient forms of energy transmission in nature.

It is the net motion of the particles that causes a vibration. **Net motion** is the displacement of a particle over a certain time interval. The particle may follow a complex path, but the particle's net motion is how far it has moved (straight-line distance) from its starting point to its finishing point. After a wave has passed through a medium, the particles return to their original location. Ideally, there is no net motion of the particles when they have stopped vibrating, so their net displacement is zero. Therefore, no work is done on them by the wave—no energy is lost by the wave and it can continue indefinitely. **Figure 2** illustrates this point. The boat is going up and down when a wave passes, but the boat does not move with the wave energy.

vibration the cyclical motion of an object about an equilibrium point

mechanical wave the transfer of energy through a material due to vibration

medium the material that permits the transmission of energy through vibrations

net motion the displacement of a particle over a certain time interval; the difference between the particle's initial and final positions

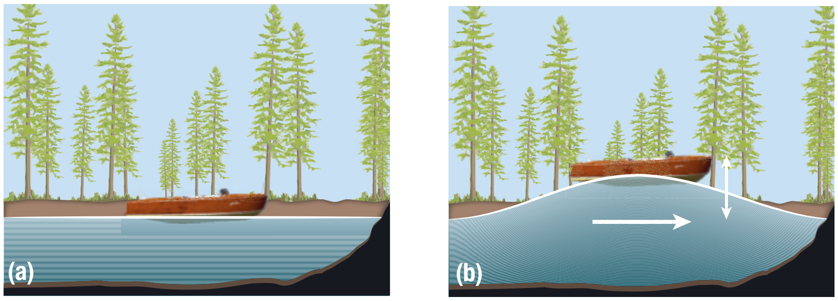


Figure 2 A boat on a lake does not move to shore due to wave action alone. After the wave passes, the boat returns to its position in (a).

Particle Behaviour in Different Media

Recall from previous science courses that molecules are always in motion because of thermal energy. However, thermal motion—motion resulting from thermal energy—is random and does not produce a transfer of energy in the form of a mechanical wave. Instead, the medium has to be disturbed by a vibration to set up a mechanical wave. **Figure 3** illustrates this concept using the example of the drumhead from page 378.

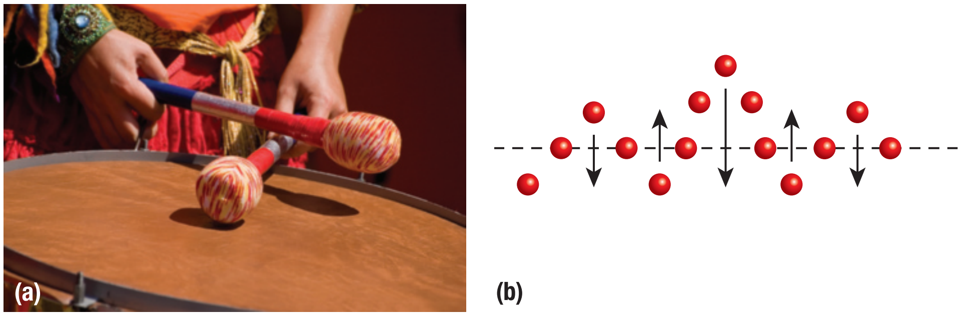


Figure 3 (a) After the musician strikes the drum, a mechanical wave transfers energy outward from the impact point. The wave travels through the medium; in this case, the skin of the drumhead. (b) The particles of the drumhead vibrate and transfer their motion to particles beside them. This allows the wave energy to move through the medium.

All vibrations need a medium to transfer waves. A medium's effectiveness at transmitting vibrations varies, depending on its molecular and mechanical structure, its density, and even its temperature. We now examine more closely how the behaviour of particles in different media allows energy to be transferred by vibrations.

Particle Behaviour in Solid Media

Suppose you sit at one end of a mattress, and at the other end you place some objects such as textbooks. If you bounce on one end of the mattress, the objects at the other end will move. This is because the material in the mattress is connected, so a disturbance at one end is transferred to the other end.

In a solid medium, the atoms are held securely in a crystal formation by strong intermolecular forces. Therefore, they can only vibrate slightly as the disturbance passes through the medium. If the medium returns to its original shape after the disturbance, the medium is said to be **elastic**. Most solid media have this property—even very rigid media, such as steel. In general, rigid materials transfer mechanical waves more efficiently than less rigid materials. Thus, mechanical waves in rigid materials last longer, go faster, and go farther than they do in less rigid media. During an earthquake, for example, vibrations through rigid media like rock can be transmitted thousands of kilometres from the source (**Figure 4**). You will learn more about earthquakes in Chapter 10.

Conversely, the less rigid a medium, the less efficient it is at transferring a vibration. A less rigid material, such as a pillow, disperses more energy through absorption, so a vibration weakens quickly. The speed and distance that a wave can travel are therefore reduced.

elastic the property of a medium that returns to its original shape after being disturbed

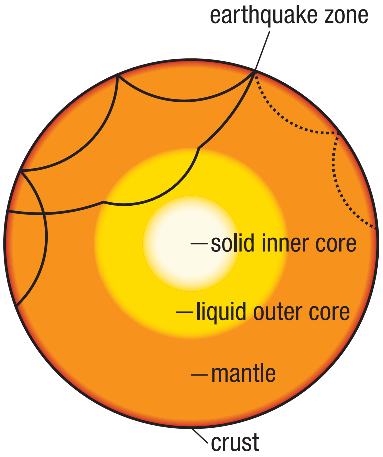


Figure 4 A cross-section of Earth during an earthquake shows how the waves pass through the planet.

Particle Behaviour in Fluid Media

Recall that liquids and gases are classified as fluids because they are materials that can flow. In liquids, the molecules are not in a crystal formation but are still very much in contact. So liquids are very effective transmitters of sound. For example, sound travels almost five times as fast and much farther in water than in air.

The individual molecules in a gas are much farther apart than they are in liquids and solids. Consequently, gas is the least dense state of matter. Gases rely on **translational molecular motion**, or straight-line motion, to transfer vibrations.

translational molecular motion the straight-line motion of a molecule; this motion is typical of gases because the particles in liquids and solids are not free to move in this manner

With their lower density, gases are less effective than solids and liquids at transmitting vibrations. How well a gas transmits a vibration also depends on the gas's temperature and density. **Figure 5** illustrates particle vibration in a solid, a liquid, and a gas.

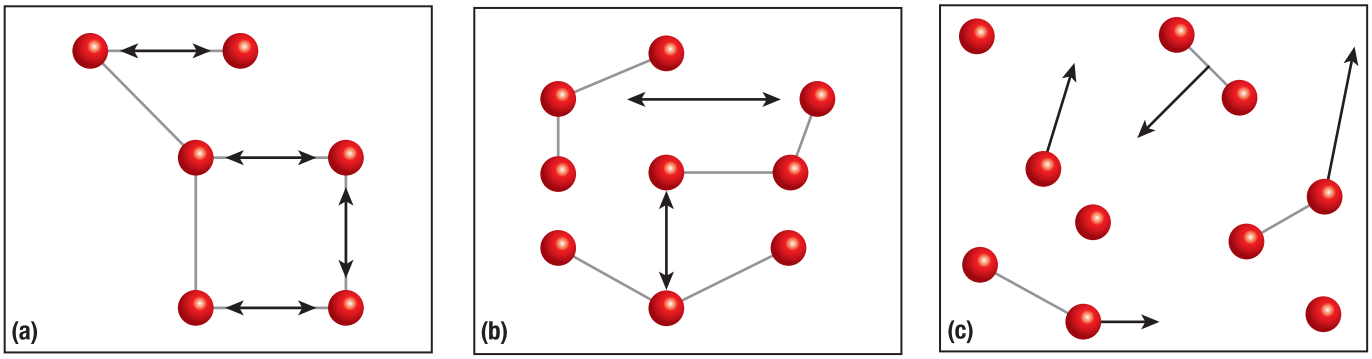


Figure 5 Microscopic particle vibration in (a) a solid, (b) a liquid, and (c) a gas. Solid and liquid media are generally more effective at transmitting vibrations than gases are.

8.1 Summary

- A vibration is the cyclical motion of an object about an equilibrium point.
- All vibrations need a medium to transfer waves.
- A mechanical wave is a transfer of energy through a medium by particle vibration. Particle vibration is caused by a disturbance to the medium.
- A medium is a material that permits the transmission of energy due to vibrations. A medium can be a solid, a liquid, or a gas.
- The particles of an elastic medium return to their original location after a wave passes through.
- The speed of a wave and the distance it can travel depend on the composition of the medium. A rigid medium allows a wave to travel longer and faster than a less rigid medium. A less rigid medium disperses more energy, thus reducing the speed and distance that a wave can travel.

UNIT TASK **BOOKMARK**

How could you apply information about vibrations to either the structure you research or the device you make in the Unit Task on page 486?

8.1 Questions

1. In your own words, explain the difference between a wave and a vibration. K/U
2. List five vibrating objects that you have observed or experienced in everyday life. K/U C A
    (a) Describe each vibrating object, and explain how you know it is a vibration.
    (b) How many of the vibrating objects that you listed can be considered to be transmitting a mechanical wave? List them, and explain your answer.
    (c) For each object from (b), identify the medium that transmits these waves.
3. What properties of a medium allow a wave to pass through most effectively? Provide an example in your answer. K/U C
4. Describe three ways in which we use a source of vibration to create waves that are useful to society. A
5. Describe two ways that you think mechanical waves produce effects that are harmful to society. Support your answer with an example not used in Question 2. A
6. In a graphic organizer, explain the relationship between the speed of a wave in different media and the particle nature of the media. K/U C

Types of Mechanical Waves

8.2

Mechanical waves can be classified according to the direction of the particle motion compared to the direction of the wave motion. There are two basic types of mechanical waves: transverse waves and longitudinal waves.

Transverse Waves

transverse wave a wave in which particles vibrate perpendicular to the direction of the flow of energy

A **transverse wave** describes a wave in which the particles vibrate perpendicular to the direction of the flow of energy. For example, when you strum the string of a guitar, you cause the string to vibrate (**Figure 1**). The stimulus (origin of vibration) provided by your finger strumming the guitar is near one end of the guitar string. The vibration moves along the string and reflects off the far end, returns, and reflects again, and so on. However, the guitar string does not move in the direction of the energy flow. Instead, the string vibrates perpendicular to the direction of the flow of energy.

Water waves are a familiar example of transverse waves. A boat bobbing on waves moves up and down. This direction is perpendicular to the direction of the flow of energy of the water waves.

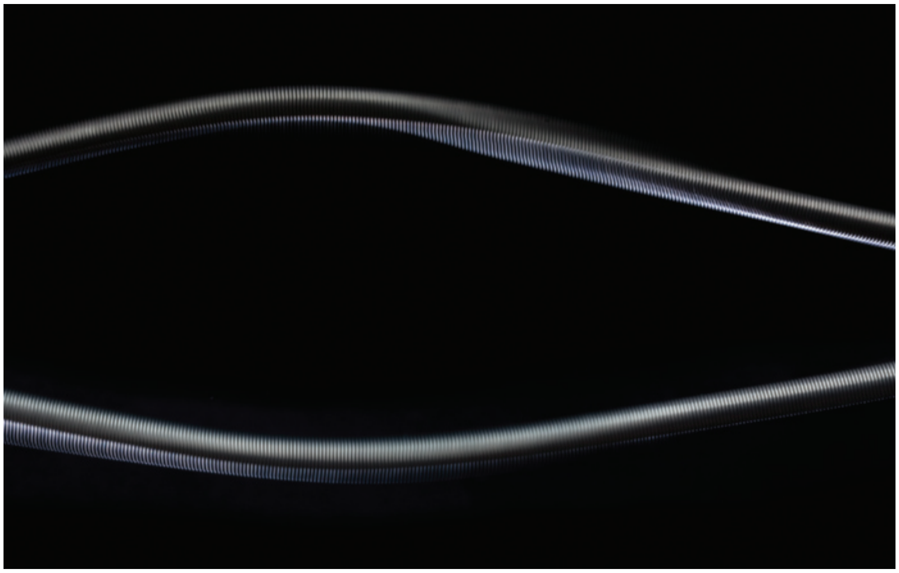


Figure 1 In this image of a single vibrating guitar string, the particles in the string are moving up and down, and the energy is flowing back and forth along the string.

Longitudinal Waves

longitudinal wave a wave in which particles vibrate parallel to the direction of the flow of energy

A **longitudinal wave** describes a wave in which the particles vibrate in the same direction as the energy flow. If you performed the activity at the beginning of this chapter, you created longitudinal wave motion in a Slinky by sending pulses along the length of the Slinky. A pulse is a single wave or single disturbance. **Figure 2** illustrates a longitudinal wave.

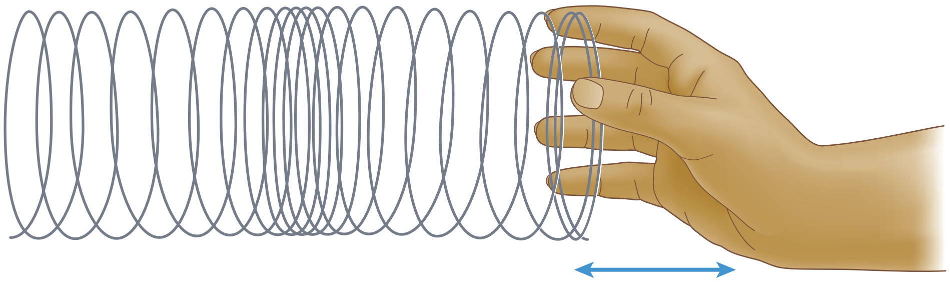


Figure 2 Longitudinal wave motion in a Slinky

Another way to demonstrate a longitudinal wave is to connect a number of masses together with springs, as shown in **Figure 3**. If you pull mass A to the left and then release it, the spring action will pull mass A toward mass B. The energy is transferred from mass A to mass B, then from mass B to mass C, and so on. The particles transferring the energy—the springs or the masses—all move parallel to the direction of the flow of energy.

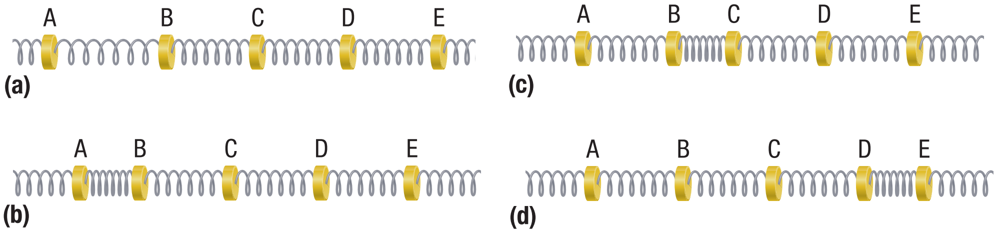


Figure 3 (a) Mass A is pulled to the left and released. (b) Masses A and B move closer together, moving the energy from the stimulus along the springs and masses. (c) The vibration moves along causing masses B and C to be closer. (d) The wave has now made it to mass E. In the entire transfer, the particles have all moved parallel to the direction of the flow of energy.

compression the region in a longitudinal wave in which the medium's particles are closer together

rarefaction the region in a longitudinal wave in which the medium's particles are farther apart

Compressions and Rarefactions

Gas molecules have much greater freedom of movement, and they are in constant motion due to their temperature. A longitudinal vibration in a gas results in regions where the particles are closer together, called **compressions**, and regions where they are farther apart, called **rarefactions** (Figure 2).

The terms "compression" and "rarefaction" correspond to the local pressure differences as the wave's energy passes through the medium. When the particles are closer together, or compressed, the pressure is increased above ambient pressure. The term "ambient pressure" describes the average pressure of the gas; that is, the pressure it would have if the wave were not present. The regions where particles are farther apart, or rarefied, have a pressure that is lower than ambient pressure. This concept is illustrated in **Figure 4**.

LEARNING **TIP**

Rarefaction

The term "rarefaction" may be new to you, but you may have heard the term "rarefied" used to describe the air at high altitudes, where a passenger jet flies, for instance. At an altitude of 9000 m, the air is much less dense than at sea level, so we say this less dense air is rarefied. "Rarefied" comes from the word "rare," which has two older meanings: "loose" and "thin."

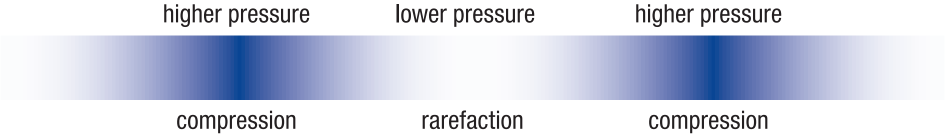


Figure 4 Rarefaction and compression regions in a longitudinal wave correspond to regions of pressure differences.

sound a form of energy produced by rapidly vibrating objects detectable by sensory organs such as the ear

Sound

A vibrating object can produce longitudinal waves in a part of the medium that surrounds it. If these waves have properties that make them detectable to the human ear, they are called **sound**. The energy transferred through successive compressions and rarefactions of a sound wave causes vibrations in our ears that the brain interprets as sound. (Human hearing is discussed further in Chapter 10.) Sound is also transmitted through liquids and solids. Our ears are less suited to detecting sound waves in liquids and solids, however. In fluids, sound is transmitted as a longitudinal wave. In solids, sound can be transmitted as either a transverse wave or a longitudinal wave.

Complex Wave Motion

Transverse and longitudinal waves are basic types of waves. However, in many cases, these types of waves combine to form a more complex wave. For example, water waves on the surface of a lake are largely produced by wind. The wind will impart some longitudinal motion to the water molecules, resulting in a motion of the water molecules that is oval in shape. The shape of the oval is controlled by how much the molecules move in each direction. For example, if the perpendicular motion is much greater than the motion parallel to the surface, then the oval is longer (**Figure 5(a)**).

Another example of a complex wave occurs when you strike a solid surface with a solid object. For example, suppose you strike a piece of wood with a hammer. Some molecules are driven forward, initiating a longitudinal wave. The intermolecular forces that connect to the rest of the surface also create a transverse wave that radiates out along the surface (**Figure 5(b)**).

WEB LINK

To see animations of transverse, longitudinal, and complex waves,

GO TO NELSON SCIENCE

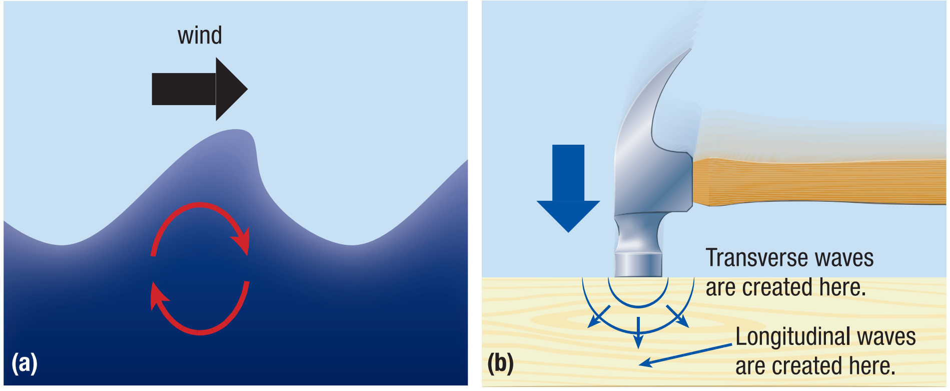

wind
(a)
(b)
Transverse waves are created here.
Longitudinal waves are created here.

Figure 5 (a) The wind blowing over the surface of water causes the water molecules to move in the shape of an oval. The shape of the oval becomes thinner and more vertical with reduced wind speed. (b) When a wood surface is struck by a hammer, the impact creates a longitudinal wave below the surface, and a transverse wave along the surface.

Mini **Investigation**

Simulating Transverse and Longitudinal Wave Motion

Skills: Performing, Observing, Analyzing, Evaluating, Communicating

SKILLS HANDBOOK **A2.1**

In this activity, you will investigate longitudinal and transverse wave motion by simulating particle motion. Your teacher will have the class move out into the hall, outside, or to some other suitably large room. Perform movements only when instructed by your teacher.

Part A: Transverse Wave Motion

1. Form a line in which all students are standing side by side, facing in the same direction. Leave approximately 1 m between yourself and the student on either side. You and your classmates represent the particles in a medium, and the space between students represents the chemical bonds. The student at one end is student 1, the student next to student 1 is student 2, and so on.
2. (a) Student 1 moves forward three steps, student 2 moves forward two steps, and student 3 moves forward one step.
   (b) Student 1 moves three steps back and returns to the starting point, student 2 moves ahead one step and then back two, and student 3 moves ahead two steps and back one step. Student 4 moves ahead three steps, student 5 moves ahead two steps, and student 6 moves ahead one step.
3. Examine the shape of the wave.
4. Repeat Step 2 with the next six students. Continue until the wave has made its way to the end. Repeat as instructed by your teacher.
5. Observe how the wave travels down the line of students.

Part B: Longitudinal Wave Motion

6. Form a line in which all students are standing one behind the other. Leave about 3 m between each student.
7. The students near one end of the line will move forward three steps. The motion is to go forward three steps and then back three steps.
   (a) The student at the back of the line is student 1, the student ahead of student 1 is student 2, and so on. Student 1 takes three steps forward. Student 2 takes two steps forward, and student 3 takes one step forward.
   (b) Student 1 takes three steps back and remains stationary from now on. Student 2 takes one step forward and two steps back. Student 3 takes two steps forward and then one step back. Student 4 takes three steps forward. Student 5 takes two steps forward, and student 6 takes one step forward.
8. Inspect the progress of the wave.
9. Repeat Step 7 with the next six students. Repeat as instructed by your teacher.

A. In the transverse wave demonstration, what did you notice about the distances between you and your neighbours? T/I

B. Did you feel it was possible to move farther than 3 m from the line, or was this difficult to accomplish? In a true medium, what would control this aspect of the wave's motion? T/I

C. In the longitudinal wave demonstration, was it difficult to maintain the motion? Why or why not? T/I

D. Were the simulations in this activity fair? What compromises were made? T/I

UNIT TASK **BOOKMARK**

How could you apply information about sound and sound waves to the Unit Task on page 486?

8.2 Summary

- In transverse waves, the particles of the medium move perpendicular to the direction of the flow of energy.
- In longitudinal waves, the particles of the medium move parallel to the direction of the flow of energy.
- In a fluid, longitudinal waves transfer energy through regions of higher and lower pressure. These regions are called compressions and rarefactions, respectively.
- Sound, an important example of a longitudinal wave, is a form of energy produced by rapidly vibrating objects.
- Many wave motions in nature are a combination of longitudinal and transverse motion.

8.2 Questions

1. In your own words, describe the characteristics of the two basic types of mechanical waves. Make a labelled diagram of each. K/U C
2. Provide two examples of transverse waves that you have encountered in everyday life. Explain why each example is considered a transverse wave. K/U C A
3. Provide two examples of longitudinal waves that you have encountered in everyday life. Explain why each example is considered a longitudinal wave. K/U C A
4. In sports stadiums an activity called the "wave" is sometimes performed by the crowd. Is this a true mechanical wave? If not, what compromises are being made with respect to the definitions given in this section? K/U
5. Define sound, and explain how a medium can transfer sound waves efficiently. K/U C
6. Is sound a mechanical wave? Explain your answer. K/U T/I
7. Aside from communicating by speech, list three benefits of being able to detect sound. A
8. Provide two examples of a complex wave motion. Describe the wave motions, and explain how you know that transverse and longitudinal waves are present. K/U C A
9. **Figure 6** is an image of an electric ringer inside a bell jar. A vacuum pump can be connected to the jar. You turn the ringer on, and slowly start removing the air from the bell jar. Then you slowly allow the air back in. K/U T/I
   (a) Predict how the sound from the ringer will change as you remove the air and then as you allow the air back in.
   (b) Explain why the sound will change.

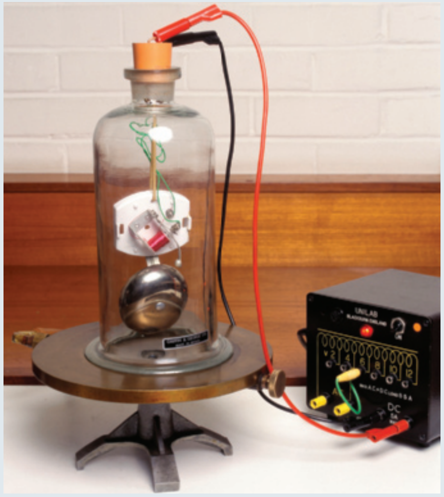


Figure 6 The connection to evacuate the air is hidden from view.

Wave Characteristics

8.3

Some characteristics of waves, such as the large water wave in **Figure 1**, are based on geometric features, and some characteristics of waves are based on time. So waves can be described in terms of their size, their shape, and the speed at which they move.

Figure 1 The characteristics of this water wave can be described in terms of its height and its speed.

Geometric Wave Characteristics

Wave characteristics based on shape and size include amplitude, wavelength, phase, and phase shift.

Amplitude and Wavelength

In Section 8.1 you learned that vibrating particles in a medium create a wave, and that the equilibrium point in a vibration is halfway between the maximum distances that an object vibrates. The maximum displacement of a vibrating particle in a wave from its equilibrium point is called the **amplitude** (**Figure 2**). Since a vibrating particle passes the equilibrium point twice each cycle, the amplitude is half the distance between the maximum and minimum values. For transverse mechanical waves, the amplitude is measured in metres.

amplitude the maximum displacement of a wave from its equilibrium point

The **waveform**, or shape of a wave when graphed, in Figure 2 shows that the maximum point of a transverse wave is called a **crest**, and the minimum point of a transverse wave is called a **trough**. A continuous wave has many repeating crests and troughs. The amplitude of a longitudinal wave, such as a sound wave, is measured by the varying pressures it creates. So scientists define the amplitude of a longitudinal wave as the maximum pressure it creates compared to the pressure of the non-disturbed medium. For this reason, longitudinal waves are often referred to as pressure waves.

waveform the shape of a wave when graphed

crest the maximum point of a transverse wave

trough the minimum point of a transverse wave

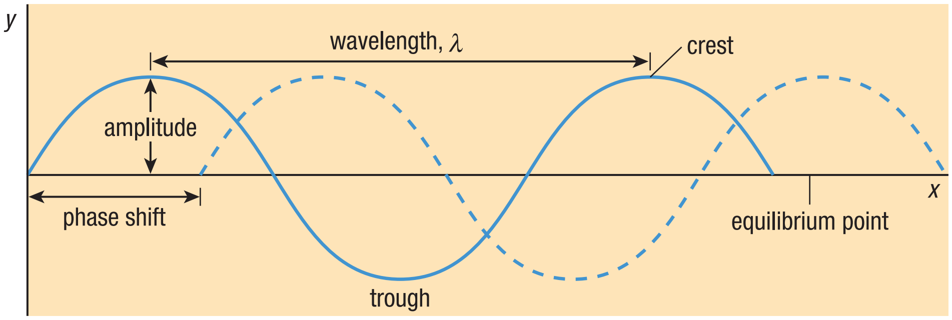


Figure 2 Geometric wave characteristics applied to both transverse and longitudinal waves. Sometimes, longitudinal waves are sketched as transverse waves to make them easier to observe.

Also shown in Figure 2 is wavelength. **Wavelength** is the distance between two similar points in successive identical cycles in a wave (such as from crest to crest or from trough to trough). The symbol for wavelength is the Greek letter lambda, λ (pronounced LAM-da).

wavelength (λ) the distance between two similar points in successive identical cycles in a wave, such as from crest to crest or trough to trough

Phase and Phase Shift

In both transverse and longitudinal waves, the *x*-coordinate of a unique point of a wave is called its **phase**. The units of phase are the same as the units of wavelength (metres). Phase can also be expressed as a decimal percentage. Thus, halfway through a single cycle is a phase of 0.5 (no units).

Two waves can be identical to each other but shifted along the *x*-axis with respect to each other. A **phase shift** is a shift of an entire wave with respect to an identical wave along the *x*-axis, usually by some fraction of a single wavelength (Figure 2).

phase in a continuous transverse or longitudinal wave, the *x*-coordinate of a unique point of the wave

phase shift a shift of an entire wave along the *x*-axis with respect to an otherwise identical wave

So a phase shift of $\frac{\lambda}{2}$ (or a phase shift of 0.5) means that the crest of one wave is opposite a trough in the other. This is a very important concept in electricity, electronics, the physics of sound (Chapter 9), and the study of the atom.

in phase the state of two identical waves that have the same phase shift

out of phase the state of two identical waves that have different phase shifts

Identical waves are **in phase** if their phase shifts are equal, and **out of phase** otherwise. The amount they are out of phase is equal to the phase shift. Often, if two waves are $\frac{\lambda}{2}$ out of phase, they are simply said to be "totally out of phase."

Time-Based Wave Characteristics

Time-based wave characteristics are related to the motion of the vibrating particle and the wave. These characteristics are frequency, period, and the speed at which a wave travels.

Frequency, Period, and Speed

frequency (*f*) the number of complete cycles that occur in unit time, usually 1 s; measured in hertz (Hz)

period (*T*) the time for a vibrating particle to complete one cycle

The number of complete cycles per unit time, usually 1 s, is called the **frequency (*f*)** (**Figure 3**). A wave has the same frequency as the vibrating particles that create and sustain it. The SI unit of frequency is the hertz (Hz) and is defined as one cycle per second.

The time it takes for any of the vibrating particles in a wave to complete one cycle is called the **period (*T*)**. When studying waves, the vibration of the particles is often difficult to observe, so the period can be found by measuring the length of time it takes for one wavelength to pass by a fixed point, or the time it takes for one complete vibration. Frequency and period are related mathematically:

$$\text{frequency} = \frac{\text{cycles}}{\text{unit time}} \qquad \text{period} = \frac{\text{time}}{\text{unit cycle}}$$

Consequently,

$$f = \frac{1}{T} \text{ and } T = \frac{1}{f}$$

LEARNING TIP

Period

The term "period" is also used in other repeating motions, such as revolutions and rotations, to indicate the time for one cycle.

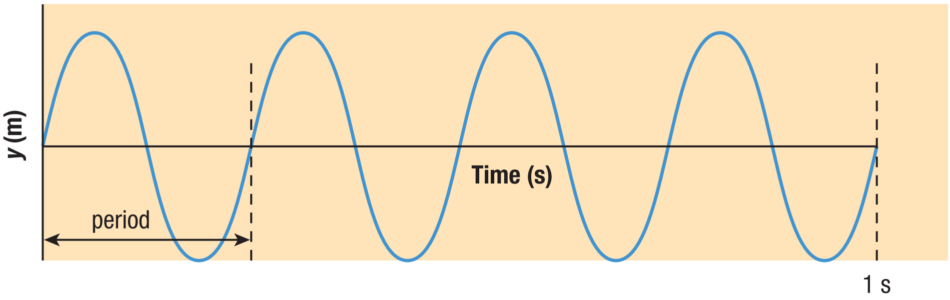


Figure 3 Wave characteristics based on time. Frequency is the number of complete cycles per second. Here, there are about $4\frac{1}{4}$ crests per second, so the frequency is $f \approx 4.25$ Hz. The period is $T \approx 0.235$ s.

wave speed (*v*) the rate at which a wave is travelling through a medium; also a measure of how fast the energy in the wave is moving

If you stay in one spot and measure how fast the wave crests are passing by, you will have a measure of the **wave speed (*v*)**. The speed of a wave is also a measure of how fast the energy in the wave is moving. If you know the wavelength and the period of a wave, you can calculate wave speed. As you learned in Chapter 1, speed is calculated by dividing the distance (wavelength, in this case) by time (period). Hence,

$$v = \frac{\lambda\,(\text{m})}{T\,(\text{s})} = \frac{\text{length of one cycle}}{\text{time for one cycle}}$$

The unit of wave speed is metres per second (m/s). As you will learn in Section 8.4, how fast a wave moves depends on the medium in which it is travelling as well as the temperature of the medium.

Simple Harmonic Motion

One common type of oscillation (vibration) is called simple harmonic motion (SHM). **Simple harmonic motion** is any motion that repeats itself at regular intervals about an equilibrium point. The amplitude, period, and frequency are the same for each oscillation. Examples of SHM are spring-mass systems (**Figure 4**), a simple pendulum oscillating with a small amplitude, a particle vibrating within a solid, and driven oscillators, such as wave machines.

Investigation **8.3.1**

Investigating Vibrations (p. 402)
In this investigation, you will hypothesize the factors that affect transverse and longitudinal motion and then test your hypotheses.

simple harmonic motion any motion that repeats itself at regular intervals

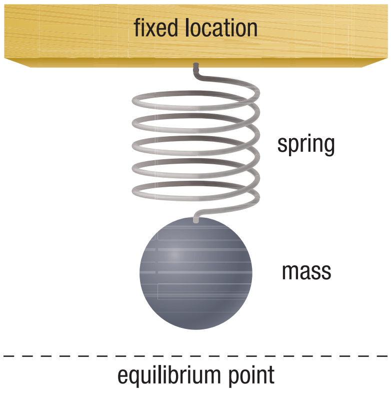


Figure 4 A spring-mass system

8.3 Summary

- Wave characteristics are based on both wave shape and the behaviour of a wave in time.
- Amplitude is the maximum distance a vibrating particle moves from its equilibrium point.
- Wavelength is the distance between two similar points in successive identical cycles in a wave, such as from crest to crest or trough to trough.
- The phase shift is the amount that one waveform is displaced along the x-axis from an otherwise identical waveform.
- Frequency is the number of complete cycles of a wave that occur per unit of time (usually 1 s). Period is the time it takes for a vibrating particle to complete one cycle.
- Wave speed is the rate at which a wave travels through a medium. It is also a measure of how fast the energy in the wave is moving.
- Simple harmonic motion (SHM) is any oscillating motion that repeats itself at regular intervals.

8.3 Questions

1. Copy **Figure 5** into your notebook. K/U

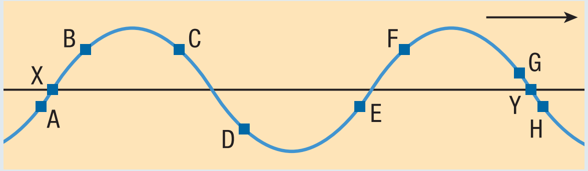


Figure 5

   (a) Label the amplitude, wavelength, and equilibrium point of the waveform.
   (b) List all pairs of points that are in phase.

2. Contrast wavelength and amplitude for (a) longitudinal waves and (b) transverse waves. K/U C
3. In your own words, distinguish between wave speed and frequency. K/U C
4. Make a sketch that shows two identical transverse waveforms, except one waveform is phase-shifted one-half a wavelength from the other. K/U C A
5. Make a sketch that shows two identical longitudinal waveforms, except one waveform is phase-shifted one-half a wavelength from the other. K/U C A
6. If you did the activity at the beginning of this chapter, you performed a simple demonstration of two types of wave motion using a Slinky. Do you think that these motions were examples of simple harmonic motion? Explain your answer. K/U T/I C

8.4 Determining Wave Speed

In this section, you will learn about the mathematical relationships involved with wave speed, such as the universal wave equation. You will also learn what factors influence the speed of a wave; in particular, a sound wave.

The Universal Wave Equation

Imagine you are standing on a dock on a lake so that you are able to observe the passing waves. (You can assume that you have all the equipment necessary to allow you to observe and measure properties of waves, such as distance and time.) First, by timing the duration between crests passing your reference point, you can measure the period of the wave. Then you can take a picture of the waveform and measure the wavelength using the dock and other structures as distance references. From these measurements, you can calculate wave speed using the kinematics definition for average speed.

$$v = \frac{\lambda}{T}$$

Using the fact that frequency is the reciprocal of period, a substitution can be made for T in the wave speed equation:

$$f = \frac{1}{T}$$

$$v = \frac{\lambda}{\frac{1}{f}}$$

$$\boxed{v = f\lambda}$$

LEARNING **TIP**

Reciprocal
A reciprocal is a number that you multiply by so that the result equals 1. For example, the reciprocal of 4 is $\frac{1}{4}$ because $4 \times \frac{1}{4} = 1$.

universal wave equation $v = f\lambda$

This important relationship is called the **universal wave equation**, and it is valid for all waves and wave types.

The universal wave equation can also be derived as follows:

$$\text{frequency } (f) = \frac{\text{cycles}}{\text{time}}$$

$$\text{wavelength } (\lambda) = \frac{\text{distance}}{\text{cycles}}$$

$$\begin{aligned}\text{frequency } (f) \times \text{ wavelength } (\lambda) &= \frac{\cancel{\text{cycles}}}{\text{time}} \times \frac{\text{distance}}{\cancel{\text{cycles}}} \\ &= \frac{\text{distance}}{\text{time}} \\ &= \text{wave speed } (v)\end{aligned}$$

Hence

$$v = f\lambda$$

Tutorial 1 demonstrates how wave speed can be calculated using the universal wave equation.

Investigation **8.4.1**

Investigating Two-Dimensional Wave Motion (p. 403)
In this investigation, you will predict the relationships between frequency, speed, and wavelength.

Tutorial **1** Using the Universal Wave Equation

Sample Problem 1: Calculating Wave Speed

A harp string supports a wave with a wavelength of 2.3 m and a frequency of 220.0 Hz. Calculate its wave speed.

Given: $\lambda = 2.3$ m; $f = 220.0$ Hz

Required: v

Analysis: In this example, both λ and f are given. So, to solve this problem, substitute for the variables and calculate the answer using the universal wave equation: $v = f\lambda$

Solution:

$$\begin{aligned} v &= f\lambda \\ &= (220.0\ \text{Hz})(2.3\ \text{m}) \\ v &= 506\ \text{m/s} \end{aligned}$$

Statement: The wave speed on the harp string is 506 m/s.

Sample Problem 2: Calculating Wavelength

A trumpet produces a sound wave that is observed travelling at 350 m/s with a frequency of 1046.50 Hz. Calculate the wavelength of the sound wave.

Given: $v = 350$ m/s; $f = 1046.50$ Hz

Required: λ

Analysis: Rearrange the universal wave equation to solve for wavelength: $v = f\lambda$

Solution: $v = f\lambda$

$$\begin{aligned} \lambda &= \frac{v}{f} \\ &= \frac{350\ \text{m/s}}{1046.50\ \text{Hz}} \\ \lambda &= 0.33\ \text{m} \end{aligned}$$

Statement: The wavelength of the sound wave coming from the trumpet is 0.33 m.

Practice

1. If a wave has a frequency of 230 Hz and a wavelength of 2.3 m, what is its speed? T/I
   [ans: 530 m/s]
2. If a wave has a speed of 1500 m/s and a frequency of 11 Hz, what is its wavelength? T/I
   [ans: 140 m]
3. If a wave has a speed of 405 m/s and a wavelength of 2.0 m, what is its frequency? T/I
   [ans: 2.0×10^2 Hz]

Factors That Affect Wave Speed

The transfer of energy using waves is more efficient if the particle vibrations do not absorb much energy. For example, a more rigid object such as a soccer ball tends to bounce more effectively if it is fully inflated. If the atoms comprising an object are linked by strong intermolecular forces, the wave energy is transmitted more efficiently and thus the wave speed is faster. If these forces are not as strong, then energy transmission is less efficient and thus slower.

Temperature

In the case of gases, you might think that cooler gases are more effective at transmitting sound because they are denser. However, usually the converse is true because, with an increase in temperature, the molecules move faster and transfer their kinetic energy more efficiently (**Figure 1**).

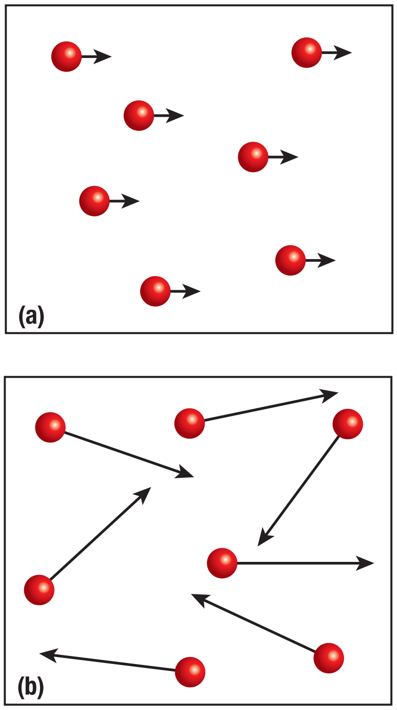


Figure 1 Comparing transmission of sound through (a) a cool gas and (b) a warm gas. The warm molecules jostle neighbouring molecules more rapidly, thus increasing the rate of sound energy transfer.

Linear Density and Tension

linear density (μ) the mass per unit distance of a string; units are kilograms per metre (kg/m)

The speed of a wave along a string, such as a violin or guitar string, is governed by the properties of the string (**Figure 2**). A string's **linear density**, or mass per unit distance, determines how much force it will take to make the string vibrate. Linear density, μ, is calculated using the equation

$$\mu = \frac{m}{L}$$

where m is the mass of the string, in kilograms, and L is its length, in metres.

Another variable affecting wave speed is tension. A loose string, for example, will quickly absorb all of the energy. A taut (tight) string, however, will transmit energy very effectively. Linear density and tension are the only variables that control the speed that waves can travel along a string. The equation for the speed of a wave along a string is

$$v = \sqrt{\frac{F_T}{\mu}}$$

where F_T is the tension in the string (in newtons) and μ is the linear density (in kilograms per metre). In Tutorial 2 we will demonstrate how this equation is used to determine the properties of a string.

Figure 2 The diameters of the guitar strings shown here are getting progressively larger from left to right. The linear density is therefore increasing from left to right. The speed of sound is progressively slower in these strings.

Tutorial 2 Determining String Properties

Sample Problem 1: Determining String Tension

On your class wave machine, you have a string of mass 350 g and length 2.3 m. You would like to send a wave along this string at a speed of 50.0 m/s. What must the tension of the string be?

Given: $m = 350$ g or 0.350 kg; $L = 2.3$ m; $v = 50.0$ m/s

Required: F_T

Analysis: First, calculate the linear density, μ. Second, rearrange the equation for the speed of a wave on a string to solve for the tension, F_T: $\mu = \frac{m}{L}$; $v = \sqrt{\frac{F_T}{\mu}}$

Solution:

$$\begin{aligned}
\mu &= \frac{m}{L} \\
&= \frac{0.350\ \text{kg}}{2.3\ \text{m}} \\
\mu &= 0.152\ \text{kg/m} \quad \text{(one extra digit carried)} \\
v &= \sqrt{\frac{F_T}{\mu}} \\
v^2 &= \frac{F_T}{\mu} \\
F_T &= v^2\mu \\
&= (50.0\ \text{m/s})^2(0.152\ \text{kg/m}) \\
&= 380.4\ \text{N} \\
F_T &= 380\ \text{N}
\end{aligned}$$

Statement: The required tension of the string on the wave machine is 380 N.

Practice

1. If a 2.5 m long string on the same wave machine has a tension of 240 N, and the wave speed is 300 m/s, what is the mass of the string? T/I [ans: 6.7×10^{-3} kg]
2. If a wave machine string has a linear density of 0.2 kg/m and a wave speed of 200 m/s, what tension is required? T/I [ans: 8×10^{3} N]
3. If a string on a wave machine has a linear density of 0.011 kg/m and a tension of 250 N, what is the wave speed? T/I [ans: 1.5×10^{2} m/s]

8.4 Summary

- The universal wave equation, $v = f\lambda$, relates the speed of a wave to its frequency and wavelength. The universal wave equation applies to all waves.
- More rigid intermolecular forces allow for a faster transfer of energy, and therefore a higher wave speed in a medium.
- Waves travel faster in hotter gases than in cooler gases because of the increased molecular motion caused by the higher temperature in a hotter gas.
- The speed of a wave on a string depends on the linear density of the string and the string's tension: $v = \sqrt{\frac{F_T}{\mu}}$

UNIT TASK **BOOKMARK**

How could you apply your understanding of the speed of sound in different materials to the Unit Task on page 486?

8.4 Questions

1. A wave has a speed of 123 m/s and a frequency of 230 Hz. What is its wavelength? T/I
2. A guitar string has a tension of 37 N. The linear density is 0.03 g/m. What is the speed of sound along this string? T/I
3. The period of a sound wave from a piano is 1.20×10^{-3} s. If the speed of the wave in the air is 3.40×10^{2} m/s, what is its wavelength? T/I
4. Earthquakes produce seismic waves, which travel through Earth. Primary waves, or P-waves, are longitudinal. They can travel through both solids and liquids. Secondary waves, or S-waves, are transverse. They can travel through solids only. P-waves travel at approximately 8.0 km/s, and S-waves travel at approximately 4.5 km/s. Following an earthquake, vibrations are recorded at seismological stations around the world. K/U T/I A
   (a) Calculate how long P-waves and S-waves take to travel from an earthquake to a seismological station that is 2.4×10^{3} km away. Express your answers in minutes.
   (b) Why do you think that transverse waves are called secondary waves?
   (c) By referring to **Figure 3**, explain how observing P-waves and S-waves helps geophysicists analyze the structure of Earth's interior.
5. Predict what happens to the wavelength of a wave on a string when the frequency is doubled. Assume that the tension in the string remains the same. Confirm your prediction mathematically. K/U T/I

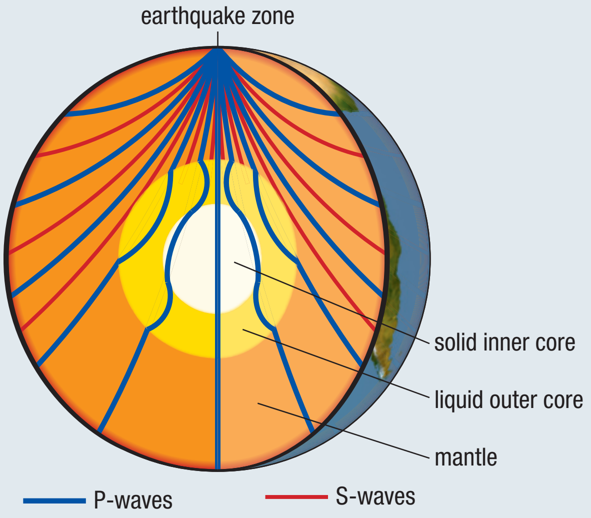


Figure 3

6. Predict what happens to the speed of a wave on a string when the frequency is doubled. Assume that the tension in the string remains the same. Confirm your prediction mathematically. K/U T/I
7. By what factor would you have to multiply the tension in a taut spring in order to double the wave speed? Confirm your answer mathematically. T/I C
8. Develop the equation for wave speed on a string. Use research if you wish. T/I C

8.5 Properties of Sound Waves

Sound waves form one of our major sensory links to the world, so it is important to understand their properties. Without sound, we would be unable to communicate by speech, hear music, or know when someone has approached us from behind.

Categories of Sound Waves

audible sound wave sound wave in the range of human hearing, 20 Hz to 20 kHz

infrasonic wave sound wave with a frequency below 20 Hz

ultrasonic wave sound wave with a frequency above 20 kHz

Sound waves fall into three categories covering different ranges of frequencies. **Audible sound waves** lie within the range of sensitivity of the human ear, approximately 20 Hz to 20 kHz for healthy young adults. The human ear is most effective at detecting sound in the range of 1 kHz to 5.5 kHz. **Infrasonic waves** have frequencies below the audible range. Earthquake waves are an example of infrasonic waves (Chapter 10). **Ultrasonic waves** have frequencies above the audible range for humans.

Applications of Ultrasonic Waves

Ultrasonic waves (ultrasound) are widely used in medical applications, both as a diagnostic tool and in certain treatments. Internal organs can be examined using the images produced by the reflection and absorption of ultrasonic waves. Although ultrasonic waves are far safer than X-rays, their images may not have as much detail.

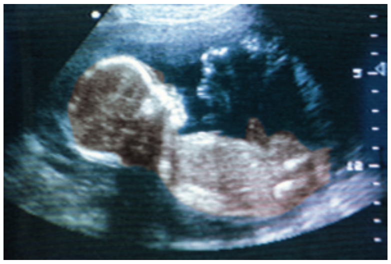


Figure 1 This ultrasound image shows a healthy fetus, about 6 months old.

Physicians commonly use ultrasound to observe fetuses (**Figure 1**). This technique presents far less risk than using X-rays, which deposit more energy in cells and can produce birth defects. An image of the fetus is obtained by using a transducer placed on the mother's abdomen, which emits the ultrasonic waves. The waves reflect off the fetus and other tissue, and the reflected sound waves are picked up by the transducer. They are then converted to an electric signal, which is used to form an image on a fluorescent screen. Difficulties such as the likelihood of spontaneous abortion are easily detected with this technique. Fetal abnormalities such as water on the brain are also readily observed.

CAREER **LINK**

Radiologists and ultrasound technicians use ultrasound waves and computer imaging to scan patients' bodies, to gauge the progress of pregnancies, to detect tumours, and more. To learn more about these careers,

GO TO NELSON SCIENCE

Ultrasound is also used to break up kidney stones that are otherwise too large to pass. Previously, invasive surgery was more often required.

Another application of ultrasound is the ultrasonic ranging unit used in some cameras. This unit provides an almost instantaneous measurement of the distance between the camera and the object to be photographed. The principal component of this technology is a crystal that acts as both a loudspeaker and a microphone. An ultrasound pulse is transmitted from the transducer to the object, which then reflects part of the signal, producing an echo that is detected by the device. An **echo** is the sound that reflects off a surface back to the device (or person) that produced the sound. The time interval between the outgoing pulse and the echo is electronically converted to a distance, using the known quantity of the speed of sound.

echo the sound energy reflected off a surface back to the producer of the sound

Research This

Using Ultrasound Technology in Medicine

Skills: Researching, Analyzing, Communicating SKILLS HANDBOOK A5.1

A relatively new medical application using ultrasound technology is the cavitron ultrasonic surgical aspirator (CUSA).

1. Research this technology using the Internet and/or print resources.

A. What does this technology do? K/U

B. Explain how this technology works. K/U C

C. Why is this technology preferred over traditional surgery? T/I C

GO TO NELSON SCIENCE

The Speed of Sound

It has been determined experimentally that the speed of sound through air depends on the density of the air and its temperature. This value increases by 0.606 m/s for every increase of 1 °C. Using the equation below, you can calculate the speed of sound in air at different temperatures:

$$v = 331.4 \text{ m/s} + (0.606 \text{ m/s/°C})T$$

where *T* is the temperature in degrees Celsius. Tutorial 1 shows how to calculate the speed of sound in air using this equation.

Investigation 8.5.1

Measuring the Speed of Sound (p. 404)

In this investigation, you will predict the speed of sound on a certain day and then measure it. Make sure you understand how the equation for calculating the speed of sound works.

Tutorial 1 Calculating the Speed of Sound

Sample Problem 1: Determining the Speed of Sound at a Certain Temperature

The temperature outside is 23 °C. What is the speed of sound in air at this temperature?

Given: $T = 23 \text{ °C}$

Required: v

Analysis: The information given can be directly substituted into the equation for the speed of sound in air: $v = 331.4 \text{ m/s} + (0.606 \text{ m/s/°C})T$

Solution:

$$\begin{aligned} v &= 331.4 \text{ m/s} + (0.606 \text{ m/s/°C})T \\ &= 331.4 \text{ m/s} + (0.606 \text{ m/s/°C})(23 \text{ °C}) \\ v &= 345 \text{ m/s} \end{aligned}$$

Statement: The speed of sound in air at 23 °C is 345 m/s.

Sample Problem 2: Determining Air Temperature

If the speed of sound is measured to be 318 m/s, what is the current air temperature?

Given: $v = 318 \text{ m/s}$

Required: T

Analysis: To solve for the temperature of the air, rearrange the original equation. Then substitute the given variable and calculate the answer: $v = 331.4 \text{ m/s} + (0.606 \text{ m/s/°C})T$

Solution:

$$\begin{aligned} v &= 331.4 \text{ m/s} + (0.606 \text{ m/s/°C})T \\ T &= \frac{v - 331.4 \text{ m/s}}{0.606 \text{ m/s/°C}} \\ &= \frac{318 \text{ m/s} - 331.4 \text{ m/s}}{0.606 \text{ m/s/°C}} \\ T &= -22.1 \text{ °C} \end{aligned}$$

Statement: The temperature of the air is −22.1 °C.

Practice

1. If the temperature of the air in your region is 32 °C, what is the speed of sound in air at that temperature? T/I [ans: 351 m/s]
2. If the speed of sound near you is 333 m/s, what is the ambient temperature? T/I [ans: 2.64 °C]
3. If the speed of sound near you is 350 m/s, what is the ambient temperature? T/I [ans: 31 °C]

Mach Number

Ernst Mach (1838–1916), an Austrian physicist, researched sound waves and devised a way to describe air speeds of objects in terms of the speed of sound. Mach's approach relates the local speed of sound and the airspeed (speed relative to the surrounding air) of an object, such as an aircraft. (Section 8.6 describes what happens when aircraft travel at the speed of sound, as well as the history of aircraft attempting to reach that speed.) The ratio of the airspeed to the local speed of sound is called the **Mach number**:

Mach number (*M*) the ratio of the airspeed of an object to the local speed of sound

$$M = \frac{\text{airspeed of object}}{\text{local speed of sound}}$$

Note that the ratio has no units. For this reason, when describing the speed of an object using the Mach number, we say Mach 1, Mach 2, and so on. Mach 1, for instance, means that the object is travelling at the speed of sound. An aircraft's Mach number is not fixed—it changes depending on the speed of sound in its vicinity. For example, an aircraft travelling at fixed speed from Helsinki, Finland, to Havana, Cuba, would have different Mach numbers at the two places because of different air temperatures and pressures. Tutorial 2 shows how to calculate Mach numbers.

Tutorial 2 Calculating the Mach Number

Sample Problem 1

An aircraft is flying at 905 km/h in air at the temperature −50.0 °C. Calculate the Mach number associated with this speed.

Given: $T = -50.0\ ^\circ\text{C}$; $v = 905\ \text{km/h}$

Required: M

Analysis: Calculate the speed of sound in air at a temperature of −50.0 °C. The speed of the airplane must be converted into metres per second and the calculation made using the Mach number equation.

Solution:

$$\begin{aligned} v &= 331.4\ \text{m/s} + (0.606\ \text{m/s/}^\circ\text{C})T \\ &= 331.4\ \text{m/s} + (0.606\ \text{m/s/}^\circ\text{C})(-50.0\ ^\circ\text{C}) \\ v &= 301.1\ \text{m/s (one extra digit carried)} \end{aligned}$$

$$905\ \frac{\cancel{\text{km}}}{\cancel{\text{h}}} \times \frac{1000\ \text{m}}{1\ \cancel{\text{km}}} \times \frac{1\ \cancel{\text{h}}}{3600\ \text{s}} = 251.4\ \text{m/s}$$

$$\begin{aligned} M &= \frac{\text{airspeed of object}}{\text{local speed of sound}} \\ &= \frac{251.4\ \text{m/s}}{301.1\ \text{m/s}} \\ M &= 0.835 \end{aligned}$$

Statement: The Mach number is 0.835.

Practice

1. If the local speed of sound is 344 m/s and an aircraft is flying at 910 km/h, what is the Mach number? T/I [ans: 0.73]
2. If the Mach number is 0.93 and the local speed of sound is 320 m/s, what is the speed of an airplane in these conditions? T/I [ans: 3.0×10^2 m/s = 1100 km/h]
3. If the Mach number is 0.81 and the speed of an airplane measured by radar is 850 km/h, what is the local speed of sound in kilometres per hour? T/I [ans: 290 m/s = 1.0×10^3 km/h]

The Speed of Sound in Various Media

As you learned in Section 8.4, waves travel more rapidly in certain solids (rigid intermolecular forces) and in hotter gases than in cooler gases. Thus, the speed of sound depends not only on the temperature of the medium but also on the medium's properties. **Table 1** lists the speed of sound in different media.

Table 1 Speed of Sound in Various Media

Medium	Speed of sound (m/s)
air (20 °C)	344
air (0 °C)	331
air (−20 °C)	319
glass (Pyrex)	5170
steel	5000
water	1496
wood (maple)	4110

Sound Intensity

Loudness describes how humans perceive sound energy. Loudness depends on a quantity called sound intensity.

It is important to think about how humans experience the transfer of energy in a wave. In Section 8.2, you learned that sound energy is a longitudinal wave and that the amplitude of a longitudinal wave is a difference in pressure. **Pressure** is defined as the force per unit area. Mathematically,

$$p = \frac{F}{A}$$

pressure (*p*) the force per unit area

You have also learned that waves transfer energy. The amplitude of a wave is an indirect measure of how much energy the wave is transferring. So, for a sound wave, the larger the amplitude, the louder the sound you perceive. This energy transfer is also related to area. Recall from Chapter 5 that the rate of energy transfer is called power and its unit is the watt (W). The amount of sound energy being transferred per unit area is called the **sound intensity**. The units of sound intensity are watts per square metre, or W/m^2.

sound intensity the amount of sound energy being transferred per unit area; unit W/m^2

Human Perceptions of Sound Intensity

In terms of sound intensity, the threshold of hearing ranges from about 1×10^{-12} W/m^2 to about 1 W/m^2—a range of approximately 12 magnitudes. A more convenient way to deal with this large range is to use a unit called the **decibel** (dB). The decibel is one-tenth of a bel, symbol B. This unit is named in honour of Alexander Graham Bell, the inventor of the telephone. When using decibels, we refer to sound level, instead of sound intensity. For example, the difference between sound intensities of 10^{-12} W/m^2 and 10^{-8} W/m^2 is 10 000 units. This is expressed as a difference of 40 dB (or 4 bels). An increase in 3 dB is actually a doubling of the sound energy. The decibel gives measurements on a scale of about 0 to 100, with exceptionally loud sound levels exceeding 100, but rarely exceeding 200. **Table 2** shows sound intensities along with their equivalents in decibels from the threshold of human hearing up to sound intensities that are very dangerous to humans.

decibel (dB) the unit of sound level used to describe sound intensity level

LEARNING **TIP**

Logarithms

The unit bel is logarithmic. A logarithm is the exponent of 10 that would produce a given number. For example, if $x = 10^y$, then y is the base 10 logarithm of x. As y increases by 1, x increases by a factor of 10.

Table 2 Typical Sound Levels

Type of sound	Typical sound intensity (W/m^2)	Sound level (dB)	Type of sound	Typical sound intensity (W/m^2)	Sound level (dB)
threshold of human hearing	1×10^{-12}	0	jet flyover (at 300 m)	1×10^{-2}	100
normal breathing (at 1 m)	1×10^{-11}	10	rock band	0.1	110
typical whisper (at 1 m)	1×10^{-10}	20	jet aircraft engine (at 80 m), power saw	1.0	120
empty classroom	1×10^{-9}	30	threshold of pain	10	130
computer (at 1 m)	1×10^{-8}	40	military jet taking off	100	140
library	1×10^{-7}	50	space shuttle (at 180 m)	316	145
alarm clock (at 1 m)	1×10^{-6}	60	sound cannon (at 1 m)	1 000	150
vacuum cleaner (at 2 m)	1×10^{-5}	70	1 tonne TNT (at 30 m) (buildings 50 % destroyed)	380 000	175.8
diesel locomotive (at 30 m)	1×10^{-4}	80	tornado	1×10^{12}	240
motorcycle (at 10 m)	1×10^{-3}	90	atomic bomb	1×10^{13}	250

Mini Investigation

Testing Loudness

Skills: Planning, Performing, Observing, Analyzing, Communicating

SKILLS HANDBOOK A1.2, A2.1

Equipment and Materials: sound level meter or decibel meter

1. Measure the sound levels of music from a car stereo system or radio using the sound meter. Start at low loudness levels, and then increase the level to the value you normally use.

Do not listen to sustained loud sounds; they may damage your hearing.

2. Record the readings, and compare them to the values listed in Table 2.

A. Summarize your findings in a short report. Include a safety warning for this activity. T/I C

Loudness and Distance

You will have noticed that the farther you are from a sound, the quieter it becomes. As a sound wave expands from its source, the total energy it carries stays about the same, but the area of air that it acts upon increases greatly with distance. Therefore, the energy per unit area decreases, and your ear detects a quieter sound. **Table 3** shows examples of how distance affects the perceived loudness (sound level) we hear. Notice that the loudness drops off very quickly, but audible levels stay for quite a distance. However, as the distance increases, the sound level continues to decrease, but at a much-reduced rate. This is why you can hear aircraft that are 8 km in the air and fireworks in the distance.

Table 3 Loudness as a Function of Distance

Distance (m)	Sound level (dB)
1	120
10	100
50	86
100	80
200	74
500	66
1 000	60
2 000	54
5 000	46
10 000	40

Sound Safety

Any sound levels greater than 100 dB that persist for more than a few minutes will harm your hearing. If your job exposes you to such levels, you should wear hearing protection. Equipment for detecting loudness levels must be carefully calibrated. Such equipment is used to ensure safe working conditions as well as to monitor sound levels required for delicate equipment that can be damaged by high sound levels.

It is also important to realize that the louder a sound, the less time you can spend near it without damaging your hearing. **Table 4** shows some values of exposure time as a function of loudness. Notice that the times drop dramatically with louder sounds.

CAREER LINK

An audio technician operates and maintains audio equipment during such events as media broadcasts and theatrical performances. To learn more about becoming an audio technician,

GO TO NELSON SCIENCE

Table 4 Sound Exposure Times

Continuous dB	Permissible exposure time
85	8 h
88	4 h
91	2 h
94	1 h
97	30 min
100	15 min
103	7.5 min
106	3.75 min (<4 min)
109	1.88 min (<2 min)
112	0.94 min (~1 min)
115	0.47 min (~30 s)

8.5 Summary

- Audible sound waves range from 20 Hz to 20 kHz. Infrasonic waves have frequencies below 20 Hz. Ultrasonic waves have frequencies above 20 kHz.
- We can apply our understanding of the properties of sound to technologies that benefit society.
- The speed of sound through the atmosphere, in metres per second, is given by the relationship $v = 331.4\text{ m/s} + (0.606\text{ m/s/°C})T$, where T is the temperature in degrees Celsius.
- Sound intensity is a measure of the energy flowing through the unit area due to a sound wave.
- Human hearing can detect a range of sound intensities over many magnitudes in intensity.
- Loudness levels are usually described on the decibel scale, which is more convenient than the range of values for sound intensity. Loudness levels are dependent on the distance from the source of the sound.
- Sound levels in industry and recreation must be kept to a reasonable level to avoid hearing damage.

UNIT TASK **BOOKMARK**

You can apply what you learned about loudness to the Unit Task described on page 486.

8.5 Questions

1. Researchers at the University of Adelaide, Australia, are proposing to control cyanobacteria with ultrasound. Research this topic using Internet resources, and answer the following questions: 🌐 A
   (a) What are cyanobacteria, and why are these bacteria important to control?
   (b) How are cyanobacteria traditionally controlled?
   (c) Why does the treatment propose using low-frequency ultrasound instead of high-frequency ultrasound?
2. An aircraft is flying at Mach 2. What does this mean? K/U
3. An aircraft is travelling at Mach 0.83 in air at 10 °C. What is its speed in kilometres per hour? T/I C
4. Explain why the speed of sound varies in the different materials in Table 1 on page 395. K/U C
5. In your own words, define (a) sound intensity, (b) loudness, and (c) decibel. K/U C
6. Why are different units required for sound intensity and loudness? K/U C
7. In your own words, describe the concept of sound intensity. K/U C
8. Research the loudness level that is safe for listening to music on, for example, a personal music player. 🌐 T/I C
   (a) Is there a difference in the level depending on the length of exposure?
   (b) Suppose the volume scale of a personal music player ranges from 0 to 10. Suppose also that each level corresponds to an increase in volume of 10 dB. So volume 1 = 30 dB and volume 3 = 50 dB, and so on. What is the loudest level you should set your personal music player to if you listen to music for 2 h a day?
9. A busy city street can produce sound levels near 90 dB, depending on the number of large vehicles (**Figure 2**). Calculate the ratio of the sound intensity of a power saw to that of a city street. Refer to Table 2 on page 395. Express your answer in words. T/I C

Figure 2

10. A burglar coughs with an intensity of $2.35 \times 10^{-7}\text{ W/m}^2$. The burglar alarm is sensitive to an intensity of $1.0 \times 10^{-10}\text{ W/m}^2$ and will ring if the detected sound is 30 dB greater than its detection threshold. Will the burglar's cough be detected? T/I C
11. The federal government supports the construction of noise barriers (also called sound baffles) on the sides of highways that run through residential areas to reduce residential noise. Research highway traffic noise barriers. 🌐 K/U A
   (a) What are the barriers made of?
   (b) How do they work?
   (c) How effective are the barriers in reducing residential noise?

🌐 GO TO NELSON SCIENCE

The Sound Barrier

ABSTRACT
In the late 1940s, there was international tension between the Soviet Union and the United States. Both sides began a weapons race to outdo the other. Consequently, having faster aircraft became very important. At that time, when a pilot tried to fly an airplane near the speed of sound, significant vibrations occurred within the airplane. These vibrations caused either a loss of control or destruction of the aircraft. It was difficult to overcome this problem, but the U.S. Air Force succeeded in 1947.

Introduction

Ever since the Wright brothers flew the first airplane in 1903, many pilots and aeronautical engineers have aimed for faster air travel. The ability to fly even faster became more important after World War II, in the late 1940s, when a weapons race between the United States and the Soviet Union developed. As technology improved and engineers built aircraft that could fly faster and approach the speed of sound (343 m/s at room temperature, or about 1200 km/h), they could see that their goal was a real possibility. This turned out to be a very hazardous undertaking, however.

The sound waves emitted by aircraft build up in front of it. As the aircraft approaches the speed of sound, it starts to catch up to those sound waves. As a result, large compressions (pressure) build up in one area and form multiple shock waves in front of the aircraft. The shock waves have sufficient force to cause an aircraft to fly differently than it might at slower speeds. In fact, the shock waves can damage the aircraft or prevent the pilot from using the controls effectively. If a pilot cannot control the aircraft, the situation may become life-threatening. Overcoming this challenge is called "breaking the sound barrier."

The challenge of breaking the sound barrier led to new designs for aircraft wings. One example is the swept-wing technology featured on modern passenger jets that travel at near-sonic speeds, shown in **Figure 1**.

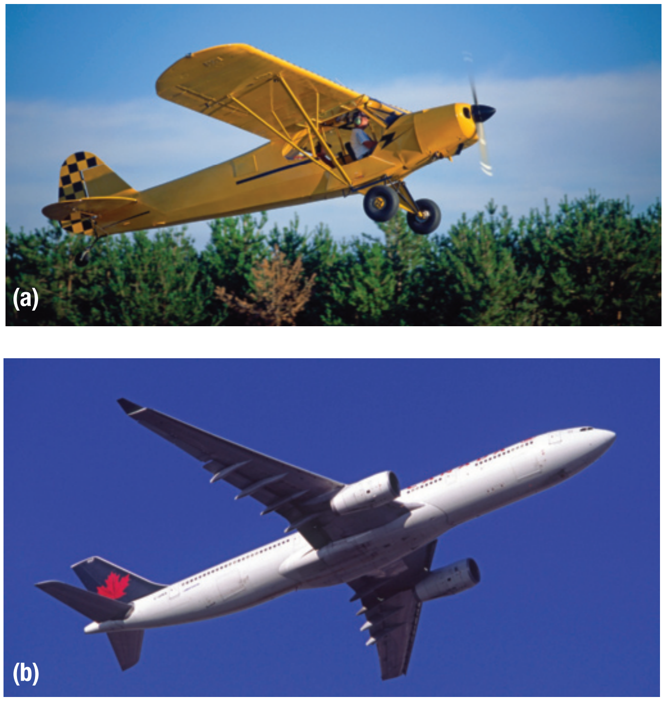


Figure 1 (a) The wings on a propeller plane are perpendicular to the airflow. (b) The wings on modern passenger jets are angled, so the airflow over the wings is smoother. The greater the sweep of the wings, the faster the airplane.

Another challenge was building a more powerful engine. Engineers were already considering the problem in the 1920s as propeller plane designs began to mature. As a propeller plane approaches or perhaps exceeds the speed of sound, the effectiveness of the propeller is reduced by as much as 50 %. Engineers discovered that, at such speeds, the shock waves cause a lot of drag (a form of frictional resistance) on the propeller blades. Thus a greater force is required to turn them faster.

In addition, the air passing by a propeller blade is deflected at a significantly lower speed than the speed of the turning propeller. So, for a propeller plane to go faster than the speed of sound (supersonic) in level flight, the propeller blade has to travel much faster than the speed of sound. Experiments showed that this increase in performance required a more powerful engine, a jet engine.

The Jet Engine

Pioneered in the 1920s, the jet engine was first made operational by British engineer Sir Frank Whittle in 1937. However, he could not interest the government in assisting his work for a number of years, so the development of the jet engine progressed slowly.

By 1936, German engineer Hans von Ohain had taken out a patent on his design for a jet engine. After impressing aircraft designer Ernst Heinkel, von Ohain was given a place in Heinkel's factory. With the assistance of some of Heinkel's best technicians, a workable engine design was fabricated. The first jet-powered plane to fly was the Heinkel He-178. It flew for the first time on August 27, 1939—a remarkably short development period from conception in 1935 to flight test barely four years later.

Parallel to the development of the jet engine was that of the rocket. German rocket designer Wernher von Braun started with basic ideas from German rocket pioneer Hermann Oberth. A large team of scientists, led by von Braun, vastly improved the technology with the development of the V-2 rocket. Given the state of the two engine technologies at the end of World War II, U.S. government engineers decided that the rocket engine was the best choice for aircraft to go supersonic.

U.S. engineers designed the shape of their supersonic test airplane, the Bell X-1, after that of a bullet, since this shape was known to go supersonic easily. Due to the lack of computer simulations and other testing available today, test piloting new aircraft at that time was dangerous. Hundreds gave their lives in this effort (about one per week in the 1950s). Despite the dangers, test pilots were willing to take chances for the adventure and to further the research.

Breaking the Sound Barrier

Chuck Yeager, a skilled World War II pilot, was asked to be the test pilot for the Bell X-1 (**Figure 2**). He took the job without a raise of his Air Force salary of $3396 a year ($34 100 in 2010, about the same as a desk clerk or a barber). Yeager was confident that his piloting skills could get him through the turbulence near the speed of sound. He had other problems, though, on the morning of October 14, 1947. The night before, he had been out horseback riding with his wife, and he fell and broke a couple of his ribs. If he told anyone on the base, he would be grounded instantly, and his backup, another brilliant pilot named Bob Hoover, would take his place. Yeager had himself treated by a local veterinarian and kept quiet about the situation.

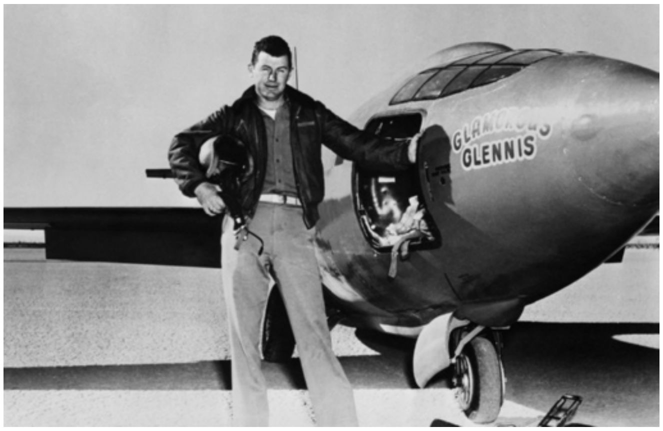


Figure 2 Chuck Yeager and the Bell X-1 were dropped from a larger aircraft at an altitude of about 6000 m. Yeager then started the Bell X-1's rocket engines. When he reached the speed of sound, the first human-made sonic boom was heard.

Later that day, Yeager and the Bell X-1 were dropped from another plane. He started the rocket engines and flew into history, reaching a peak speed of about Mach 1.07. That day, the technicians on the ground heard a loud boom—they thought the Bell X-1 had exploded. The boom was a new phenomenon, now called a "sonic boom," which happens every time an aircraft (or other object) breaks the sound barrier. Yeager's celebration was short-lived because the entire project was a national secret. His only material reward was a free dinner at a local diner.

Further Reading

Anderson, J.D., Jr. *Research in supersonic flight and breaking the sound barrier.*

Wolfe, T. (1979). *The right stuff*. New York: Farrar, Strauss and Giroux.

Yeager, C., & Janus, L. (1986). *Yeager: An autobiography*. New York: Bantam Books.

GO TO NELSON SCIENCE

8.6 Questions

1. Why did the U.S. government try to break the sound barrier? T/I
2. Why was going faster than the speed of sound so dangerous? K/U
3. What is the phenomenon that occurs when an object breaks the sound barrier? Research this topic and determine what restrictions are placed on high-speed aircraft concerning this phenomenon. T/I
4. Research the Internet and/or print resources, and find out who the first woman was to break the sound barrier. Write a short blog entry. K/U C
5. When an aircraft approaches the speed of sound, the cloud-like phenomenon seen in **Figure 3** forms. Research this phenomenon, and summarize why it happens. T/I

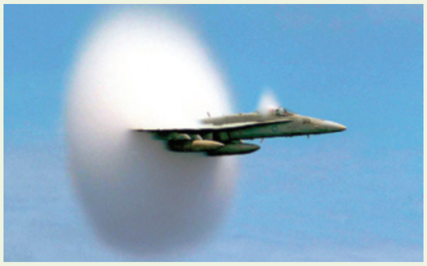


Figure 3

8.7 Explore an Issue in Sound

SKILLS MENU

- Defining the Issue
- Researching
- Identifying Alternatives
- Analyzing
- Defending a Decision
- Communicating
- Evaluating

Noise Pollution

An increase in loudness signifies an increase in energy in sound waves. If we are not careful, loudness can lead to hearing damage, whether from operating heavy equipment or from listening to music at high volumes. While machines have to work to support society, and almost everyone enjoys some form of music, we need to treat excessive sound levels with some respect to protect our hearing.

The Issue

The local government is considering enacting a new law that will place sound limits on certain activities in the community to protect the hearing of its citizens. Consider the sources of excessive sound in your community and your personal environment. They might include the following:

- farm machinery (**Figure 1(a)**)
- subway trains (especially braking) (**Figure 1(b)**)
- general and commercial traffic (city)
- construction machinery (**Figure 1(c)**)
- power tools
- motorcycle exhaust sounds (**Figure 1(d)**)
- music volume (personal music player)
- music volumes in fitness centres
- personal recreational vehicles, such as dirt bikes, all-terrain vehicles, and snowmobiles

Figure 1 (a) A combine harvester (b) A subway train (c) Construction machinery (d) A motorcycle

ROLE

You have been hired by the town council to research this topic and make recommendations to the council. You will explain your recommendations to the townspeople during a public meeting. Approach this issue from the viewpoint of a professional engineer, researching and analyzing the data and then making recommendations based on the data.

AUDIENCE

The audience is the townspeople (your classmates) and the town council. The consulting engineers will post their recommendations around the town (your classroom) to educate the townspeople on the issue. They will follow with a presentation with graphics explaining the situation in detail. Questions from the townspeople are to be expected at the end of the presentation.

Goal

To make a recommendation to the town council about enacting laws limiting sound levels for certain activities

Research

SKILLS HANDBOOK A5.1

Research this topic using Internet and print resources. In your research, include an assessment of the noise levels of the noise producers listed on page 400. Furthermore, include estimates of how far typical users are from such devices and the impact of prolonged exposure to such noise levels.

Are other towns around the world considering such a policy? Consider the position of the International Organization for Standardization (ISO), which promotes worldwide standards for product integrity and public safety. What do they recommend? How much time would you give people and organizations to make such changes? Research the term "grandfather clause," and determine if this would be effective here.

In your recommendations, assess the economic impact of your suggestions. You may be asking people to go out and buy different equipment or to change activities or procedures from those they are used to. Your research should give a sense of how large an economic impact your findings would have on people. You might also consider how important the task is to the town. For example, you could compare temporary construction work with the noise of buses, which are permanent.

WEB **LINK**

To learn more about noise pollution,

GO TO NELSON SCIENCE

Identify Solutions

In your research, you will access a lot of information, including many suggestions on how to deal with this issue. Your group will have to sort through all of these sometimes conflicting opinions and determine the recommended course of action. Your presentation should have some very specific recommendations that can be justified from the scientifically valid information. It must also include a reasonable timeline for any changes you recommend. Furthermore, it must address the expected economic impact of any changes. These can be immediate in the sense of modified or new equipment compared to long-term health benefits of the population at large.

Communicate

Write an essay of approximately 1000 words. You will be presenting the information from your essay to the class in the form of a poster or an electronic presentation, so include graphics as well. Identify which activities create a more significant hazard, perhaps by their loudness or the amount of time people are in contact with them. Explain the hazards to human health presented by exposure to excessive noise, assess their economic and personal effects, and describe protective devices and legislation. Are these adequate? Is further legislation required? Should limits be placed on sound levels for motorcycles, lawn mowers, personal music players, and so on? Should public transit operators have to muffle their engines and braking systems more effectively? Who should pay for these changes if implemented?

After giving your essay to the Mayor (your teacher), hold a Town Hall meeting, during which you will present your work to the class. Questions and public debate are to take place after the presentation. Your presentation should be posted around the town for a few days before the Town Hall meeting so that the townspeople can be made aware of your recommendations on this topic.

UNIT TASK **BOOKMARK**

You can apply what you learned about noise pollution to the Unit Task described on page 486.

Plan for **Action**

(a) Imagine that you are now a member of the town. Write a letter to the editor of the local paper describing the Town Hall meeting and your point of view. T/I C A

(b) Alternatively, consider yourself a reporter for a local newspaper or news service. Write an editorial giving your opinion of the Town Hall meeting and how you think it will affect the life of your community. T/I C A

CHAPTER 8 Investigations

Investigation 8.3.1 CONTROLLED EXPERIMENT

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Investigating Vibrations

In most waves, the rate of vibration of the particles is so rapid that it requires specialized equipment to observe it. In this investigation, you will slow the vibrations down, enabling you to observe transverse and longitudinal wave motions.

Testable Questions

- What are the relationships between (a) period and frequency, (b) wave speed and wavelength, (c) frequency and wavelength, and (d) frequency and wave speed for both a longitudinally and a transversely vibrating particle?
- What properties of a pendulum and a spring-mass system control the vibration of the particle?

Hypothesis

Make hypotheses based on the Testable Questions. Your hypotheses should be based on the theory presented in this chapter and must include a prediction and a reason for your prediction.

Variables

SKILLS HANDBOOK A2.2

After reading the Testable Questions, Experimental Design, and the Procedure, identify the controlled, manipulated, and responding variables. Determine whether the manipulated variable is truly independent of the others.

Experimental Design

In this experiment you will observe the properties of particle motion in a spring-mass system. You will measure the frequency, period, amplitude, and average particle speed for transverse and longitudinal motion.

Equipment and Materials

- digital video camera and stable platform (optional)
- stopwatch
- large retort stand and ring clamp
- 100 g and 200 g masses (other masses in this range will work as well)
- spring with $k \leq 10$ N/m
- metre stick
- fishing line or other thin string
- black tape

Procedure

1. Set up the retort stand, and attach the ring clamp as high as possible on the retort stand.
2. Tape the metre stick to the retort stand. Wrap some tape around the metre stick at decimetre intervals.
3. If you are using a video camera, set it on a stable platform.

Part A: Transverse Vibration

4. Attach one end of an approximately 1 m length of string to the retort stand where the ring clamp is attached. Attach the other end of the string to the outermost part of the ring clamp. Hang the mass from this string loop. This V arrangement ensures that the pendulum will vibrate in a single plane.

Be careful not to drop heavy objects near your feet.

5. Pull the pendulum approximately 15 cm from the vertical rod of the retort stand.
6. As the pendulum vibrates, discuss its motion with your group, and decide how to measure characteristics such as the frequency, period, amplitude, and average particle speed.
7. Record your observations from Step 6 in a data table.

Part B: Longitudinal Vibration

8. Remove the string from the retort stand used in Part A.
9. Attach a spring to the ring clamp, and suspend a 200 g mass from the spring. If the spring hits the table, hang it over the edge.

Be careful not to drop heavy objects near your feet.

10. Choose a mass so that the spring stretches no more than 10 cm downward. Pull the mass down and carefully release it so that its motion is longitudinal.
11. Measure the period, average particle speed, frequency, and amplitude. Discuss how to do this with your group, and describe your method in detail in your lab report.

Analyze and Evaluate

(a) Answer the Testable Questions. T/I

(b) Was there any change in the relationships between your results for the longitudinal and the transverse vibrations? T/I

(c) In Part A, imagine that a piece of paper was moving vertically just behind the pendulum and parallel to the plane of the pendulum's motion. Also imagine that the pendulum could make a drawing on this paper without any friction. If the paper moved upward at 1 m/s, what would the drawing on the paper look like? T/I

(d) Calculate the wave speed for the pendulum's motion including the paper's motion at 1 m/s. T/I

(e) Calculate the wavelength for the pendulum's motion including the paper's motion at 1 m/s. T/I

(f) If you wanted to double the frequency in each part of the investigation, how would you alter the pendulum? How would you alter the spring-mass system? T/I C

Apply and Extend

(g) What real-world examples of spring-mass systems can you think of? A

(h) Why do you think old clocks had pendulums? A

(i) Explain why the pendulum is not a perfect example of a transverse wave. K/U C

Investigation 8.4.1 CONTROLLED EXPERIMENT

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Investigating Two-Dimensional Wave Motion

Wave motion is not restricted to a linear medium, such as a spring or length of rope. Surfaces and solids also vibrate. In this investigation, you will examine the motion of a water wave in two dimensions under controlled conditions.

Testable Questions

- What are the relationships between (a) period and frequency, (b) wave speed and wavelength, (c) frequency and wavelength, and (d) frequency and wave speed?
- Is the universal wave equation still valid in two-dimensional wave motion?

Hypothesis

Make hypotheses based on the Testable Questions. Your hypotheses should be based on the theory presented in this chapter and should include a prediction and a reason for the prediction.

Variables

SKILLS HANDBOOK A2.2

Read the Testable Questions, Experimental Design, and Procedure. Identify the manipulated, controlled, and responding variables. Are the manipulated variables truly independent?

Experimental Design

You will drop a pebble into a calm body of water approximately 2 m in diameter and at least 30 cm deep, or a ripple tank. You will videotape the resulting wave motion. Then you will analyze your video in slow motion and measure the characteristics of the surface waves produced.

Equipment and Materials

- digital video camera with a connection to upload the recording to a computer
- computer with video-viewing program that has slow motion or preferably stop-frame display
- light source (optional)
- large container or a ripple tank
- metre stick
- pebble or other small object that can get wet
- black tape (optional)
- flashlight (optional)

Procedure

1. Ensure that there is no wind or other phenomena that will affect the water motion.
2. Assemble and prepare the recording equipment.
3. Place a metre stick near the water in such a way that it will not interfere with the water's motion or the video camera's sight lines. Depending on the expected resolution of the recording, you may want to put black tape around the metre stick at decimetre intervals.
4. Be ready with the pebble or other item to drop into the water.
5. Start the video recording and then drop the pebble. Record the movement of the water until it stops. The view of the crests can be enhanced if a light source is shone parallel to the surface.
6. Upload the video recording to a computer.
7. Develop and apply analysis methods in order to determine characteristics such as frequency, period, wavelength, and wave speed of the water waves.

Analyze and Evaluate

(a) Answer the Testable Questions. T/I

(b) Were your hypotheses correct? Explain why or why not. T/I

(c) Determine whether the universal wave equation is verified by the data you collected. T/I

(d) Determine what variables might affect the results you obtained in this investigation. What modifications to the procedure might enable you to obtain more precise results in the future? T/I

Apply and Extend

(e) This investigation is not well suited for precise measurements of amplitude, but its general trend may be evident from the video recording. That is, you may have noticed that the amplitude of the wave got shorter as it radiated outward. Considering what you have learned in this chapter, why might the amplitude decrease as it moves outward? T/I C

Investigation 8.5.1 OBSERVATIONAL STUDY

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Measuring the Speed of Sound

As you learned in Section 8.5, the speed of sound is temperature dependent. In this investigation, you will measure the speed of sound. If you wish, you can measure it on a number of days so that the temperature dependency can be analyzed. This investigation uses a football field or park area with a clear length of 100 m to 150 m. A small group of students will go to the far end with walkie-talkies (optional) and a "clapper" device, described below. The clapper will create a loud sound, and the students at the opposite end will time how long the sound takes to reach them. Choose a day that has fair weather and limited winds.

Purpose

To measure the speed of sound near your school

Equipment and Materials

- clapper: two pieces of 1" × 3" × 3' strapping connected by a small hinge at the ends so that they can be slapped together (best if painted white) (**Figure 1**)

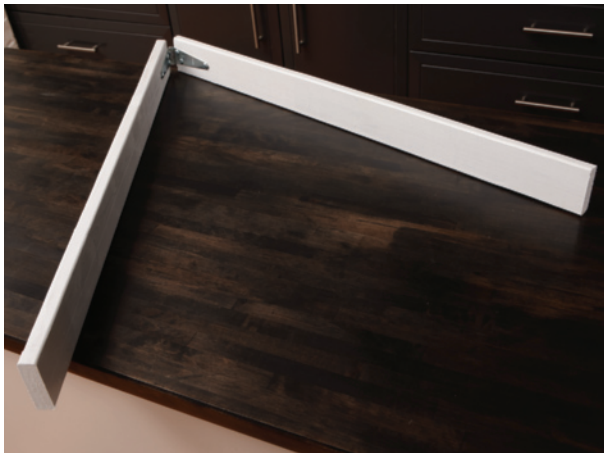


Figure 1

- thermometer
- walkie-talkies (optional) or signal flag
- 50 m measuring tape
- clipboards
- earplugs
- stopwatches
- notepaper

Procedure

SKILLS HANDBOOK A2.4

1. Prepare a table like **Table 1** to record your data. The column headings need to reflect your data and the times involved. It is best to look at your data, choose the value that is most common—the mode—and put it in the centre column of your table. If there is more than one mode, discuss with your group and your teacher how to choose the mode. Consider using spreadsheet software. "Average" is the average in a given column. "Count" is the number of values in a given column.

Table 1

	Time (s)						
	0.47	**0.48**	**0.49**	**0.50**	**0.51**	**0.52**	**0.53**
1							
2							
3							
:							
n							
Average							
Count							
% of total							

2. Measure the length of the field.
3. Measure the local air temperature.
4. Your teacher will assign three or four students to proceed to the far end of the field with the clapper device and a walkie-talkie.
5. The remaining students will operate stopwatches or record data. If walkie-talkies are unavailable, use a signal flag to indicate when the measuring and recording students are ready.
6. One student at the far end of the field will put on the earplugs and hold the "clapper" in full view of the students at the near end of the field. This student will then vigorously slap the two pieces of wood together.

Be careful of your fingers during this procedure. Do not hold the clapper too close to your or anyone else's ears.

7. If standing at the near end of the field, start your stopwatch at the instant you see the clapper come together, and stop it when you hear the sound. Record the time on your stopwatch.
8. Repeat as required until a reasonable amount of data has been collected.

Analyze and Evaluate

(a) Count the number of values in each column. Depending on how the data are spread, you may be able to use some statistics to determine how precisely you can state your results. T/I

(b) Calculate the average in each column. T/I

(c) Calculate the percentage of all measurements that a given column represents. T/I

(d) Choose the column that has the most measurements. Divide this percentage in half, and then go to the left and right of it until you have covered 34 % of the measurements on both sides. You can do this by adding half the percentage of the centre column and then the percentages to the left and right until you get to about 34 % each way. T/I

(e) How many columns did you have to move over? T/I

(f) When you calculate the average of the centre column, the one with the most values in it, how many digits can be kept? The answer in experimental science is not to guess but to look at the spread of the data as you have been doing in the steps above. Now take the number of columns you had to move to the right and left of centre and average them. (For example, you moved 4 columns to the left to obtain 34 % and 3 to the right, so the average is 3.5 columns.) Round this to one significant digit. This digit suggests that you have 2 or 3 of the measurements inside this range. In future studies this range will be very important. If this range is less than 0.1, keep two decimal places from the centre average. What is your final value for the time? T/I

(g) Using the final value you obtained for the time, calculate the speed of sound. T/I

Apply and Extend

(h) What other observations have you made in previous science classes where you were not sure how many decimals to keep? How has your opinion changed, and why? T/I C

(i) What variables in this experiment were not controlled very well? How can this be changed without adding significant expense? T/I C

(j) If you were to do this experiment again, what would you change to obtain the most precise results? T/I

(k) Your analysis can be enhanced by using the statistical concept of standard deviation (σ). This is a measure of the spread of a set of numbers that measure the same variable. There is a complicated formula for σ, but most calculators and all spreadsheet programs already have this formula programmed as a function. In one such program it is STDEV. Explore this function with either your calculator or a computer, and analyze the results of using it with your timing data. T/I

(l) If time permits, perform this study at different air temperatures and attempt to verify the temperature dependency given in Section 8.5: T/I

$$v = 331.4\ \text{m/s} + (0.606\ \text{m/s/°C})T$$

LEARNING TIP

In this investigation, you learned how a highly variable dataset can produce more precise results than you might have thought possible. This is an introduction to the science of statistics. Scientists and technologists frequently use statistical methods to guide their activities.

CHAPTER 8 SUMMARY

Summary Questions

1. Create a study guide based on the points in the margin on page 376. For each point, create three or four sub-points that provide further information, relevant examples, explanatory diagrams, or general equations.
2. Look back at the Starting Points questions on page 376. Answer these questions using what you have learned in this chapter. Compare your latest answers with those that you wrote at the beginning of the chapter. Note how your answers have changed.

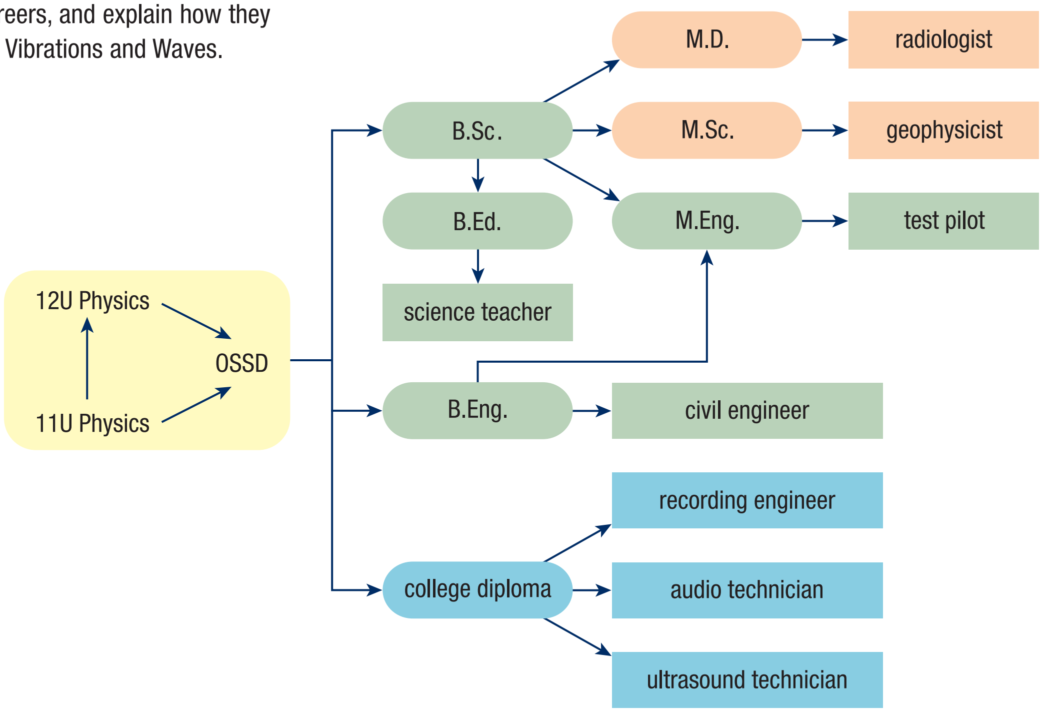
Vocabulary

vibration (p. 378)
mechanical wave (p. 378)
medium (p. 378)
net motion (p. 378)
elastic (p. 379)
translational molecular motion (p. 379)
transverse wave (p. 381)
longitudinal wave (p. 381)
compression (p. 382)
rarefaction (p. 382)
sound (p. 382)
amplitude (p. 385)
waveform (p. 385)
crest (p. 385)
trough (p. 385)
wavelength (p. 385)
phase (p. 385)
phase shift (p. 385)
in phase (p. 386)
out of phase (p. 386)
frequency (f) (p. 386)
period (T) (p. 386)
wave speed (v) (p. 386)
simple harmonic motion (p. 387)
universal wave equation (p. 388)
linear density (μ) (p. 390)
audible sound wave (p. 392)
infrasonic wave (p. 392)
ultrasonic wave (p. 392)
echo (p. 392)
Mach number (M) (p. 394)
pressure (p) (p. 395)
sound intensity (p. 395)
decibel (dB) (p. 395)

CAREER PATHWAYS

SKILLS HANDBOOK A7

1. Choose two careers that interest you and that relate to Vibrations and Waves. For each career, research the educational requirements, skills, potential employers, and salaries.
2. In a brochure, compare and contrast your two chosen careers, and explain how they connect to Vibrations and Waves.


M.D.
radiologist
B.Sc.
M.Sc.
geophysicist
B.Ed.
M.Eng.
test pilot
science teacher
12U Physics
OSSD
11U Physics
B.Eng.
civil engineer
recording engineer
college diploma
audio technician
ultrasound technician

GO TO NELSON SCIENCE

CHAPTER 8 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. What is true about particles in an elastic medium? (8.1) K/U
   (a) They are typically less effective at transferring waves than fluid media.
   (b) They are caused by a disturbance to the medium.
   (c) They return to their original location after a wave passes through.
   (d) none of the above
2. Which of the following are types of waves? (8.2) K/U
   (a) transverse and longitudinal
   (b) latitudinal and longitudinal
   (c) transverse and latitudinal
   (d) latitudinal and sound
3. Vibrations through a gas produce regions where particles are farther apart. What are these regions called? (8.2) K/U
   (a) compressions
   (b) rarefied
   (c) complex waves
   (d) rarefactions
4. Which of the following are geometric wave characteristics? (8.3) K/U
   (a) waveform, amplitude, and phase shift
   (b) amplitude, crest, and trough
   (c) crest, trough, and frequency
   (d) period, speed, and frequency
5. Wave speed is a function of
   (a) frequency and wavelength
   (b) temperature and density
   (c) frequency and amplitude
   (d) wavelength and amplitude (8.3, 8.4) K/U
6. Which of the following factors affect(s) wave speed? (8.4) K/U
   (a) linear density
   (b) temperature
   (c) tension
   (d) all of the above
7. What is the wave speed of a wave with a period of 0.50 s and a wavelength of 3.2 m? (8.4) K/U
   (a) 4.6 m/s
   (b) 5.0 m/s
   (c) 6.0 m/s
   (d) 6.4 m/s
8. Infrasonic waves have frequencies
   (a) below 20 Hz
   (b) within the range 20 Hz to 20 kHz
   (c) above 20 kHz
   (d) within the range 1 kHz to 5.5 kHz (8.5) K/U
9. The speed of sound is dependent on
   (a) the Mach number
   (b) the frequency of the sound
   (c) the temperature and density of the air
   (d) none of the above (8.5) K/U
10. The Mach number is the ratio of
    (a) force per unit area
    (b) airspeed to the local speed of sound
    (c) loudness to distance
    (d) pressure to speed (8.5) K/U

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

11. The material that permits the transmission of energy through vibrations is a mechanical wave. (8.1) K/U
12. The transmission of vibrations through a gas is subject to the gas's temperature and density. (8.1) K/U
13. A longitudinal wave is a wave in which particles vibrate in a direction that is perpendicular to the direction of the flow of energy. (8.2) K/U
14. The units of a wave's phase are the same as the unit of the wavelength. (8.3) K/U
15. Simple harmonic motion repeats itself at regular intervals. (8.3) K/U
16. Cooler gases are more effective than warmer gases at transmitting sound. (8.4, 8.5) K/U
17. Ultrasonic waves have frequencies above the human audible range. (8.5) K/U
18. As a sound wave expands from its source, the energy it contains decreases. (8.5) K/U
19. In order to prevent damage to your hearing, you should reduce your exposure time to loud sounds as the frequency of the sound increases. (8.5) K/U
20. The amplitude of a longitudinal wave is a difference in pressure. (8.2, 8.5) K/U

To do an online self-quiz,

GO TO NELSON SCIENCE

CHAPTER 8 REVIEW

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

Knowledge

For each question, select the best answer from the four alternatives.

1. What is a vibration? (8.1) K/U
   (a) the material that permits the transmission of wave energy
   (b) the cyclic motion of an object about an equilibrium point
   (c) the transfer of energy through a material
   (d) motion that repeats its path
2. What causes vibrations? (8.1) K/U
   (a) thermal energy
   (b) intermolecular forces allowing distances between atoms to vary without losing energy
   (c) the net motion of the particles in a medium
   (d) none of the above
3. Which of the following affect(s) how a medium transmits vibrations? (8.1) K/U
   (a) molecular structure
   (b) density
   (c) temperature
   (d) all of the above
4. Longitudinal vibrations in a gas form regions of
   (a) compressions and rarefactions
   (b) decompression and rarefied air
   (c) quiet and sound
   (d) none of the above (8.2) K/U
5. Water waves and waves produced by plucking string instruments are two examples of waves in which the particles vibrate in a direction that is perpendicular to the direction of the flow of energy. What are these waves called? (8.2) K/U
   (a) natural waves
   (b) longitudinal waves
   (c) transverse waves
   (d) sound waves
6. Many waves that occur in nature result in molecules being driven in directions that are both parallel and perpendicular to the direction of the flow of energy. Which type of waves are these? (8.2) K/U
   (a) transverse waves
   (b) complex waves
   (c) seismic waves
   (d) longitudinal waves
7. Which of the following is a waveform? (8.3) K/U
   (a) the minimum point of the wave
   (b) the maximum displacement of a vibrating particle
   (c) the shape of a wave when graphed
   (d) the shift of a wave with respect to an identical wave
8. The time it takes for a vibrating particle in a wave to complete one cycle is the
   (a) period
   (b) frequency
   (c) wave speed
   (d) wavelength (8.3) K/U
9. Which of the following is affected by the temperature of a gas medium? (8.4) K/U
   (a) amplitude
   (b) wave speed
   (c) period
   (d) phase shift
10. The universal wave equation applies to
    (a) complex waves
    (b) transverse waves
    (c) ultrasonic waves
    (d) all of the above (8.4) K/U
11. Which of the following are applications of ultrasonic waves? (8.5) K/U
    (a) medical diagnoses
    (b) measuring distance
    (c) medical treatments
    (d) all of the above
12. Decibels measure sound
    (a) intensity
    (b) frequency
    (c) loudness level
    (d) all of the above (8.5) K/U
13. How loud a sound is perceived is determined by the sound wave's
    (a) amplitude
    (b) frequency
    (c) wavelength
    (d) wave speed (8.5) K/U

Match each term on the left with the most appropriate description on the right.

14. (a)	wavelength	(i)	waves with frequencies above the audible range for humans
(b)	medium	(ii)	the material that permits the transmission of vibration energy
(c)	crest	(iii)	the number of complete cycles per unit of time
(d)	frequency	(iv)	the distance between two similar points in successive identical cycles
(e)	ultrasound	(v)	the maximum point of a transverse wave (8.1, 8.3, 8.5) K/U

Write a short answer to each question.

15. Vibrations and waves occur both naturally and artificially. List three examples of waves that occur naturally. (8.1) K/U
16. As the tension in a spring increases, what happens to the speed of a wave along the spring? Does the speed increase or decrease? (8.4) K/U
17. Pressure builds up in front of an aircraft as it approaches the sound barrier. What causes that increase in pressure? (8.6) K/U
18. What is noise pollution? Give an example of noise pollution not provided in the text and a suggestion for a way to reduce its effect on you or on the community. (8.7) K/U

Understanding

19. A simple pendulum is shown in **Figure 1**. Copy the figure into your notebook. Label the equilibrium point and the net displacement of the pendulum mass from its equilibrium point. (8.1) K/U

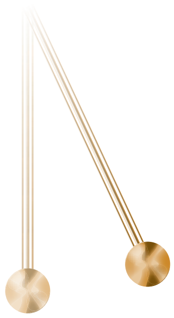


Figure 1

20. Name the state of matter that transfers vibrations through translational molecular motion. Explain why the motion is transferred in this way. (8.1) K/U
21. Explain the difference between vibrations and mechanical waves. How are they related to each other? (8.1, 8.2) K/U T/I
22. A guitar string is plucked to create a sound wave. Copy **Figure 2** into your notebook, and label the direction of the vibration of the strings and the direction of the wave. (8.2) K/U

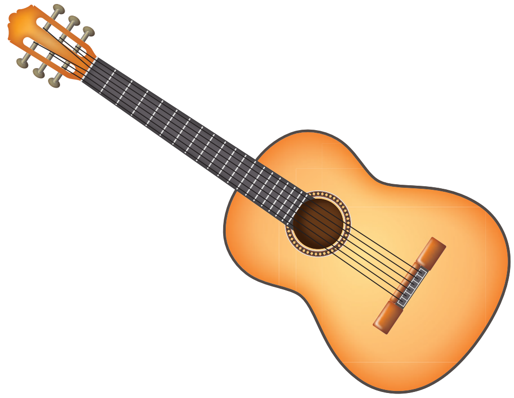


Figure 2

23. Sound moves through the air as a longitudinal wave, similar to a wave travelling along a spring. **Figure 3** shows a longitudinal wave on a spring. Copy the illustration into your notebook, and label the areas of compression and rarefaction. (8.2) K/U

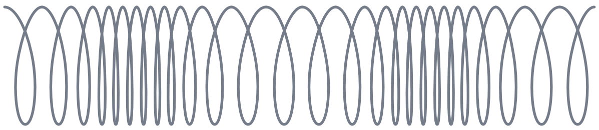


Figure 3

24. A pendulum is swinging with a period of 0.280 s. What is the frequency of the pendulum? (8.3) T/I
25. A wave has a frequency of 82 Hz. What is the period of the wave? (8.3) T/I
26. A wave on a lake has a cycle length of 0.620 m and a period of 0.300 s. What is the speed of the wave? (8.3) T/I
27. Explain how amplitude is determined in a longitudinal wave. (8.3) K/U C

28. Each part of **Figure 4** shows two identical waves experiencing a phase shift. Identify the phase shift of wave B with respect to wave A. Express the phase shift as a decimal percentage. (8.3) K/U A

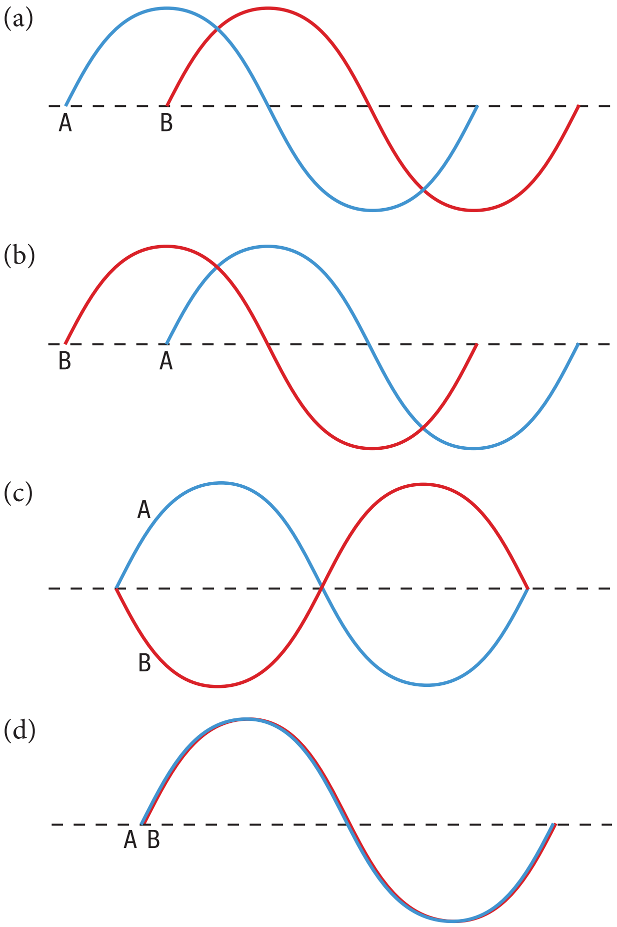


Figure 4

29. A wave has a frequency of 0.40 Hz and a cycle length of 7.0 m. What is the wave speed? (8.3, 8.4) K/U

30. A tuning fork resonates with the note A, which has a period of 0.00226 s and a wave speed of 343.2 m/s. What is the wavelength, in centimetres, of the note A? (8.3, 8.4) T/I

31. A string has a mass of 0.180 kg and a length of 1.60 m. What is the linear density, μ, of the string? (8.4) T/I

32. A string has a linear density of 0.083 kg/m and a length of 3.2 m. What is the mass of the string? (8.4) T/I

33. A string has a linear density of 0.19 kg/m at a tension of 184 N. What is the speed of a wave along the string? (8.4) K/U

34. A string has a tension of 100.0 N and a wave speed of 40.0 m/s when it is plucked. What is the linear density of the string? (8.4) K/U

35. **Figure 5** shows a guitar head. A machine head on each string is used to adjust the tension on the string. Describe how adjusting the machine head changes the wave speed produced by the string when the guitar is played. (8.4) T/I

Figure 5

36. Do waves typically travel faster in rigid media or fluid media? Explain your answer. (8.1, 8.4) K/U

37. The weather forecaster says the high temperature today is going to be 18 °C. What will the speed of sound be when the temperature reaches the day's high? (8.5) K/U

38. You do not have a thermometer to measure temperature, but you are able to measure the speed of sound through the air. If you measure the speed of sound to be 349 m/s, what is the air temperature? (8.5) T/I

39. The sound waveform displayed on the oscilloscope in **Figure 6** was produced by a tuning fork. Copy the waveform into your notebook. (8.4, 8.5) K/U C
    (a) Draw a diagram of a louder sound wave with the same frequency.
    (b) Draw a diagram of a sound wave with a higher frequency but the same loudness as in Figure 6.

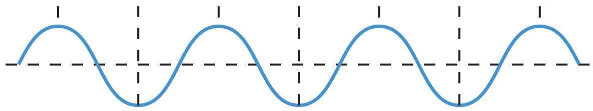


Figure 6

40. An airline passenger jet is travelling at a cruising speed of 907 km/h. If the local speed of sound is 313 m/s, what is the Mach number of the jet? (8.5) T/I

41. A plane is travelling at Mach 0.481. If the local speed of sound is 300.0 m/s, what is the airspeed of the plane, in kilometres per hour? (8.5) T/I

42. Describe why we use the decibel as a unit of sound level instead of using the actual units of sound intensity. (8.5) K/U

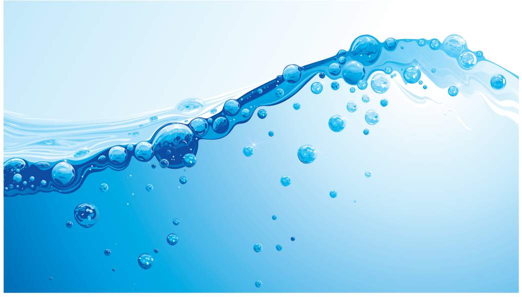
43. Why do you think aircraft were used to break the sound barrier, instead of ground-based vehicles, such as cars? (8.6) T/I

Analysis and Application

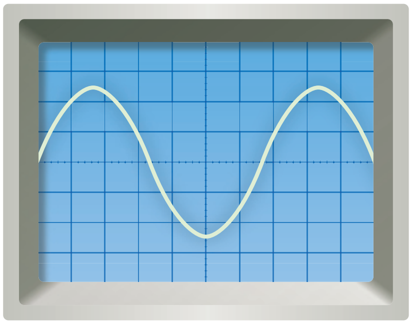
44. In science-fiction movies, the movie makers provide exciting visual and sound effects, such as the sound made by a spaceship accelerating to warp speed. Do you think if you were in space you would hear such sounds? Explain your answer. (8.1, 8.2) T/I A

45. Each image in **Figure 7** shows a wave. Copy each image into your notebook, and label the geometric wave characteristic stated. (8.3) K/U A

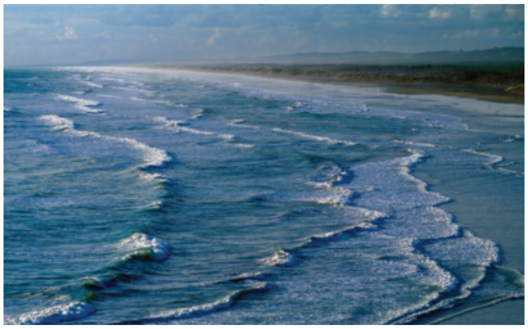
(a) crest



(b) amplitude



(c) wavelength



(d) trough

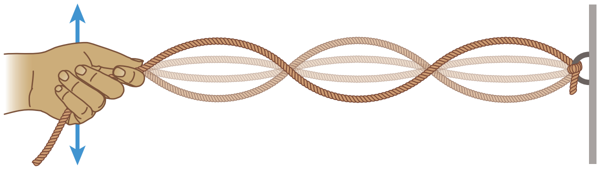


Figure 7

46. The waveform in **Figure 8** has a wavelength of 0.85 m and an amplitude of 0.25 m. Copy the figure into your notebook, and draw an identical wave with a phase shift of 0.25 m. (8.3) K/U

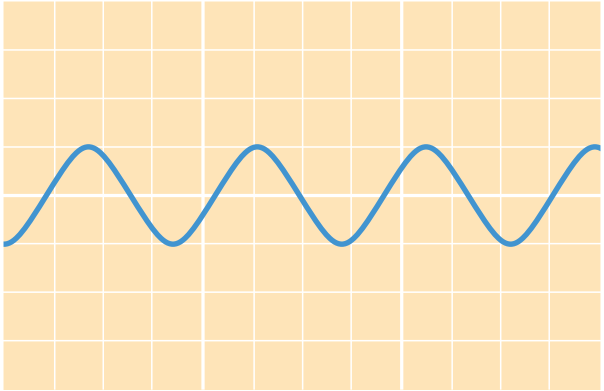


Figure 8

47. With a pendulum, the amplitude can be measured in terms of the angle made by the string at its maximum amplitude with the string at its equilibrium point. Copy **Figure 9** into your notebook, and label the amplitude of the pendulum. (8.3) K/U

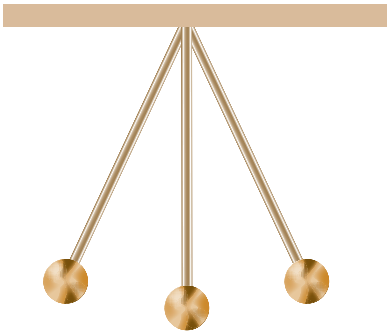


Figure 9

48. A tuning fork resonates with the note E. If the sound wave has a wavelength of 82 cm and a wave speed of 540 m/s, what is the frequency of the note E? (8.3, 8.4) T/I

49. A violin string has a wave speed of 62 m/s when it is played. If the string is 0.60 m long and has a tension of 200.0 N, what is the mass of the string? (8.4) T/I

50. A 0.220 kg string is attached to opposite sides of a room that is 4.30 m across. If the string is plucked and the resultant wave speed on the string is 18.0 m/s, what is the tension in the string? (8.4) T/I A

51. **Figure 10** shows a violin pegbox, which contains pegs that can be turned to adjust the tension in the violin strings. The string on the violin with the highest pitch is the note E, which has a frequency of 329.6 Hz and a wavelength of 1.032 m. If the string has a mass of 180.0 mg and a length of 32.0 cm and is currently producing a wave of frequency 328.1 Hz, how much do you need to change the tension in the string to produce the note E? Assume string length, string mass, and wavelength remain unchanged in the tuning process. (8.4) T/I A

Figure 10

52. The speed of sound in water is approximately 1496 m/s. Theoretically, how hot would air need to be to have the same speed of sound as water? (8.5) T/I A
53. A radio-controlled model airplane is being flown at 48.3 km/h. If the plane is being flown at Mach 0.040, what is the temperature of the air, to the nearest tenth of a degree? (8.5) T/I A
54. The SR-71 Blackbird can reach speeds above Mach 3. If the Blackbird is flying at Mach 3.00 and the air temperature is −56.0 °C, what is the speed of the aircraft, in kilometres per hour? (8.5) T/I A
55. Sound is a very common method of communication, but it requires a medium, typically atmospheric air. What are some possible methods for communicating if there is no medium? (8.3, 8.5) K/U A
56. Explain the difficulty in breaking the sound barrier with a propeller plane. (8.6) K/U
57. Traditional clocks use a pendulum and gears to maintain time. Clocks with gears have to be wound manually. More recently, quartz has been used in timepieces, which also use vibrations to keep time. When the quartz is integrated into a circuit, a voltage is applied to make it vibrate. Quartz crystals are cut and positioned so that they will vibrate at 32 768 Hz. This specific frequency is used because it is a power of 2. The number 32 768 = 2^{15}. Using such a value allows a simple calculation to get the 1 Hz needed for a clock's second hand. Quartz clocks use batteries as their energy source, instead of manual winding. How do you think this compares with traditional mechanical clocks? Explain. (8.4) T/I C
58. Our sense of hearing can be damaged by either loud noise or prolonged exposure to noise that may not be as loud. Keep a journal of the sounds that you hear throughout one day, and try to estimate the decibel level using **Table 1**. (If needed, more values are in Section 8.5, Table 2, page 395.) You will likely frequently hear human voices. Estimate the overall time and average volume level as best you can. Do you think the cumulative sound you heard is a safe amount and level? (8.5, 8.7) T/I C A

Table 1 Typical Sound Levels

Type of sound	Sound level (dB)
threshold of human hearing	0
normal breathing (at 1 m)	10
empty classroom	30
alarm clock (at 1 m)	60
vacuum cleaner (at 2 m)	70
motorcycle (at 10 m)	90
rock band	110
threshold of pain	130

59. Waves and vibrations interact with you and the environment in many ways. Pick one of the ways discussed in this chapter, other than using sound as communication between people, and discuss how the waves or vibrations affect your life. T/I C A

Evaluation

60. In this chapter, you learned about the ultrasonic ranging unit, which uses ultrasonic waves to determine distance. Assume that the ultrasonic wave has the same speed as sound at 20 °C and that the unit does not account for temperature. The average low temperature in your city in January is 5.40 °C and the average high temperature is 26.4 °C. (8.5) T/I A
    (a) If the time it takes for the wave to travel is 0.250 s, what is the range of distance from camera to subject that the unit could determine if the temperature is between those average temperatures? Hint: the camera-to-subject distance is half the distance the wave travels.

(b) Does your answer to (a) seem like a reasonable range of error? Do you think it is too great a range for this application? Explain your answer.

(c) If you were measuring smaller distances, would this range of error be acceptable?

Reflect on Your Learning

61. Was there any material, example, or problem that you found particularly interesting or helpful in this chapter? Were there any times when you felt as though a real-world situation made sense based on an explanation? K/U A

62. Do you have a basic understanding of what sound is? K/U

63. How has your understanding about sound loudness changed? Was there anything particularly relevant to you about sound loudness in this chapter? K/U C A

Research

GO TO NELSON SCIENCE

64. Ultrasound images are often used to track fetal development in the womb. Another term for ultrasound is sonography. Sonograms are images of various parts of the body. Their most effective use is to image soft tissue (**Figure 11**). Research sonography. Describe how sonography is used in medicine, and include a few examples of the organs typically imaged with this type of test. K/U C A

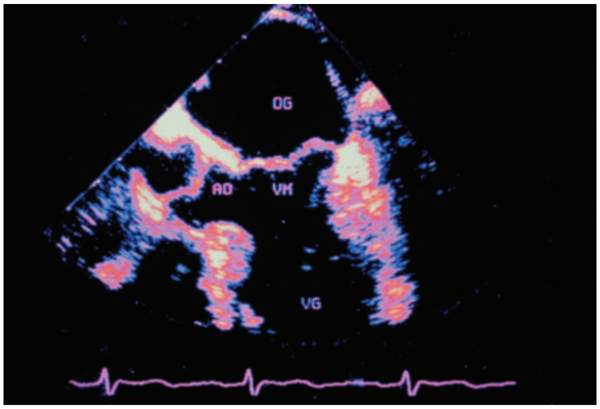


Figure 11

65. One way water waves are used is to harness energy from wave power. Research harnessing energy from wave power. List two advantages and two disadvantages of this method of energy production. A

66. One medical application of ultrasonic waves is extracorporeal shock wave lithotripsy (ESWL), which is used to treat kidney stones and gallstones. Research ESWL using the Internet and/or print resources. Explain how ultrasonic waves are used to treat these stones. T/I C A

67. Chuck Yeager is credited with being the first person to break the sound barrier in 1947 in the Bell X-1. Research and write about the history of attempts to break the sound barrier, including more recent attempts to break the sound barrier on land. T/I C

68. While there are many day-to-day applications for ultrasonic waves, infrasonic waves are not as commonly applied. One place where infrasonic waves are used is the animal kingdom. Some animals produce infrasonic sounds to communicate with each other, while others can sense infrasonic waves. Research infrasonic waves and animals. T/I C
    (a) Name two animals that use infrasonic waves.
    (b) How do they use infrasonic waves?

69. Use the Internet and other sources to research applications for infrasonic waves not described in Question 68, and describe one use. T/I C A

70. String instruments were developed independently in different areas of the world and date back thousands of years. Use the Internet and other sources to research different types of string instruments from different cultures. Compare them in a graphic organizer. T/I C

71. In the 1960s, a process called "ultrasonic welding" became commercially available. While this procedure is not exclusive to plastics, it is widely used in joining plastics for a variety of uses. Research ultrasonic welding. T/I C
    (a) Describe how ultrasonic welding works.
    (b) List some products ultrasonic welding is used to manufacture.

72. Orville and Wilbur Wright are credited with building and flying the first airplane. The Wright Flyer I had its first successful flight on December 17, 1903. However, this was not the first flight. The Wright brothers and others previously flew gliders and other experimental aircraft. Use the Internet and other sources to research the Wright brothers and their planes. Write a short report on their attempts at flight and how the Wright Flyer I was different from other earlier airplanes. T/I C

CHAPTER 9

Wave Interactions

KEY CONCEPTS

After completing this chapter you will be able to

- analyze characteristics of waves in different media
- predict what happens when waves meet each other
- classify the different types of wave interference
- understand ways in which sound interference can be used to human advantage
- understand the negative and positive effects that sound can have on the environment
- analyze standing waves in columns of air and in strings
- describe and explain phenomena such as beats, damping, resonance, and the Doppler effect

What Happens When Waves Interact with Each Other?

What do train stations, airports, rock concerts, and construction sites have in common? They are all very noisy places for the people who work there. Many people work in an environment that contains a lot of unwanted sound. In some cases, the noise is loud enough to permanently damage a person's hearing. Furthermore, it can be very difficult to hear instructions in noisy conditions. To protect workers in these situations, the easiest and least expensive solution is to use earplugs or earmuffs. Earplugs are effective, but they often block all sounds and can be uncomfortable to wear.

In the late 1980s, noise-cancelling headphones using properties of waves to reduce noise levels were introduced. Not only can these devices protect the human ear, but they can also be used to reduce damage to equipment and machinery. The technology detects the sounds near either the source or the receiver and then produces a sound wave that is completely out of phase with these sounds. The goal is to minimize the amount of unwanted background sounds.

Unwanted background sounds are eliminated in the noise-cancelling headphones, but what if you want to listen to music through the headphones? Is the music blocked too? The sound from the music is not cancelled out. Further, the sound is clearer and can be heard at lower, safer volumes with the same listening pleasure.

In this chapter, you will learn what happens when waves interact with each other. You will also learn how an understanding of the properties of waves can be applied in technologies such as noise-cancelling headphones.

STARTING **POINTS**

Answer the following questions using your current knowledge. You will have a chance to revisit these questions later, applying concepts and skills from the chapter.

1. What do you think happens when two or more water waves come together?
2. What is the basic principle behind noise-cancelling headphones?
3. Do you think a noise-cancelling system inside an airplane is beneficial? Why or why not?
4. What other situations can you think of where noise cancellation would be useful?

Mini Investigation

Media Changes

Skills: Performing, Observing, Analyzing, Communicating

SKILLS HANDBOOK A2.1

When a wave passes from one medium to another, some of the energy is reflected and some continues to the second medium (transmission). You will demonstrate this effect using different springs attached to each other.

Equipment and Materials: long narrow spring; Slinky; string

1. Connect the long narrow spring to the Slinky either by intertwining the coils or placing one inside the other and tying them together with string.
2. Lay the connected spring and Slinky out in a long, straight line on the floor, a long desk, or a table (**Figure 1**).

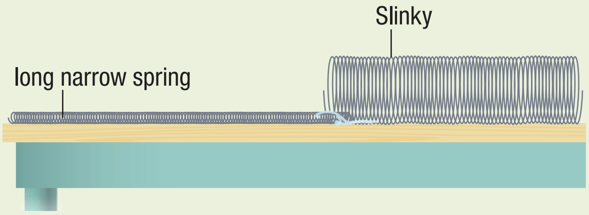


Figure 1

3. Grasp the end of the spring and give it one quick sideways jerk. Observe what happens when the wave reaches the boundary between the two springs. Record your observations.
4. Repeat Step 3, but give the end of the Slinky one quick sideways jerk. Record your observations.

A. Describe the orientation of the reflections and transmissions based on the orientation of the original pulses in Steps 3 and 4. K/U C

B. Describe the amplitudes of both waves as compared to the original wave pulses in Steps 3 and 4. K/U C

9.1 Interference of Waves

On the surface of a lake on a windy day, you will see many complicated wave motions (**Figure 1**). You will not see a simple wave moving in a particular direction. The water surface appears this way because of the action of many thousands of waves from various directions and with various amplitudes and wavelengths. When waves meet, a new wave is generated in a process called **interference**. In this section, you will learn what happens when two waves meet and interfere with each other.

Figure 1 The surface waves on this lake are the result of the interference of thousands of waves of different wavelengths and amplitudes. Most of these waves are caused by the wind, but they are also caused by passing boats and ships.

interference the process of generating a new wave when two or more waves meet

Wave Interference at the Particle Level

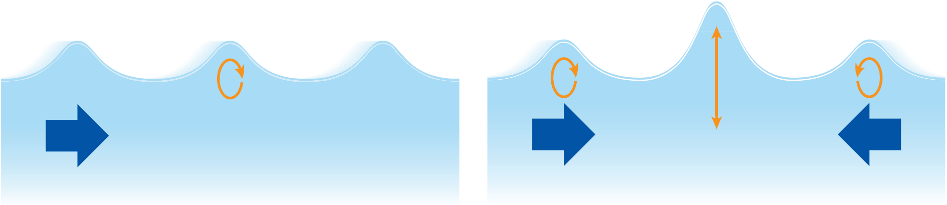
You learned in Chapter 8 that waves are the result of particle vibrations, and that the particles in a medium are connected by forces that behave like small springs. Wave interference is influenced by the behaviour of the particles.

Wave motion is efficient: in most media, little energy is lost as waves move. When waves come together, this efficiency continues. When one wave passes in the vicinity of a particle, the particle moves up and down in an oval path, which allows the wave to move in a specific direction, as shown in **Figure 2(a)**. When a second wave is also present, the vibration of the particle is modified. The oval motion of the particles stimulates the next particle in the direction of the wave's motion to begin vibrating. When two (or more) waves come together, as shown in **Figure 2(b)**, the particle moves up and down rather than in an oval path because the speeds of the combined waves cancel each other out. The motion of the particle allows the waves to pass through each other. The waves are not modified, so the amount of energy stays the same. Thus, when two or more waves interact, the particle vibration is such that the direction and energy of each wave are preserved. After the waves have passed through each other, none of their characteristics—wavelength, frequency, and amplitude—change.

WEB LINK

To see a simulation of simple interference,

GO TO NELSON SCIENCE



(a) (b)

Figure 2 (a) The basic motion of a vibrating particle in a travelling wave. (b) When two waves meet, the particle motion is more up and down. The wave characteristics are unchanged after the waves pass through each other.

Constructive and Destructive Interference

When two waves meet, the forces on their particles are added together. If the two waves are in phase (the phase shift between them is zero), then the resulting amplitude is the sum of the two original amplitudes. This is called the **principle of superposition**: the resulting amplitude of two interfering waves is the sum of the individual amplitudes. **Constructive interference** occurs when two or more waves combine to form a wave with an amplitude greater than the amplitudes of the individual waves (**Figure 3**). **Destructive interference** occurs when two or more waves that are out of phase combine to form a wave with an amplitude less than at least one of the initial waves (**Figure 4**).

principle of superposition at any point the amplitude of two interfering waves is the sum of the amplitudes of the individual waves

constructive interference the process of forming a wave with a larger amplitude when two or more waves combine

destructive interference the process of forming a wave with a smaller amplitude when two or more waves combine

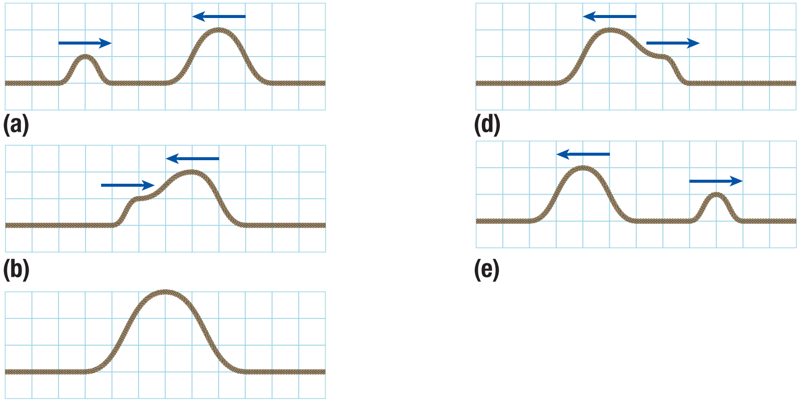

(a)
(b)
(c)
(d)
(e)

Figure 3 Constructive interference. Two wave pulses approach each other on a rope. Notice how the amplitudes of the two waves add together. Notice, also, how the waves are unchanged after they pass through each other. The amplitude during interference in (c) is the sum of the amplitudes of the two waves.

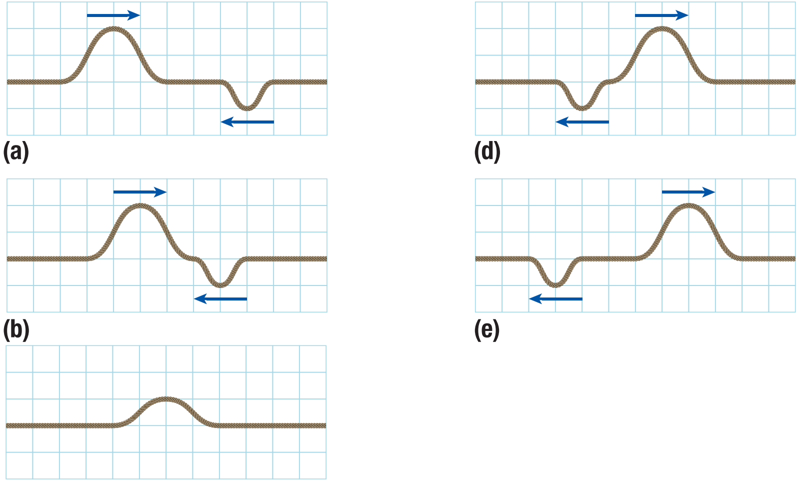

(a)
(b)
(c)
(d)
(e)

Figure 4 Destructive interference. When two wave pulses that are out of phase come together, the resulting amplitude is reduced.

Mini **Investigation**

Demonstrating Interference with Springs

Skills: Performing, Observing, Analyzing

SKILLS HANDBOOK A2.1

You can use a Slinky to demonstrate both constructive and destructive interference. In this investigation, you will observe the amplitude of waves caused by constructive and destructive interference.

Equipment and Materials: Slinky or long spring; masking tape

1. Form a small tab from the masking tape, and attach it to the middle of the Slinky.
2. With a student at each end, stretch the Slinky to an appropriate length (for example, 2.0 m).

Hold the Slinky firmly and do not overstretch it. Observe from the side, in case of an accidental release.

3. With one end held firm, send a positive pulse (a pulse where the tab moves in the positive direction) down the Slinky, noting the displacement of the tab.
4. Send a simultaneous positive pulse from each end of the Slinky, each with the same amplitude. Note the displacement of the tab.
5. Repeat Step 4, except send a positive pulse from one end of the Slinky and a negative pulse from the other.

A. Describe the amplitude the tab reached when a single pulse was sent down the Slinky. K/U

B. Describe the amplitude the tab reached when two positive pulses were sent down the Slinky from opposite ends. K/U

C. Describe the amplitude the tab reached when a positive pulse and a negative pulse were sent down the Slinky. K/U

CAREER **LINK**

Product design engineers, such as designers of audio equipment, must understand properties of sound, including interference. To learn more about becoming a product design engineer,

GO TO NELSON SCIENCE

Technology Using Interference of Waves

Noise-cancelling headphones, shown in **Figure 5**, use the concept of destructive interference. The electronics inside the headphones generate a wave that is out of phase with sound waves in the exterior environment. This out-of-phase wave is played inside the headset. Using destructive interference, the outside noise is cancelled. Such devices allow users to listen to music at lower volume levels, reducing potential damage to their hearing.

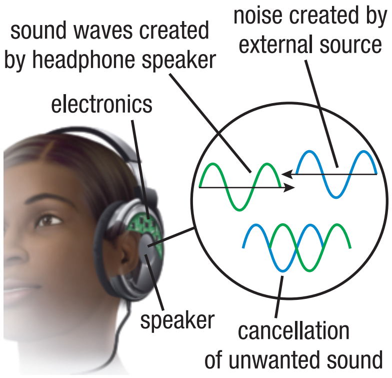

sound waves created by headphone speaker
noise created by external source
electronics
speaker
cancellation of unwanted sound

Figure 5 A detector inside the headset determines what noise there is, and a speaker in the headphone emits the out-of-phase wave.

Tutorial 1 Applying the Principle of Superposition

To determine the resulting pattern when two waves interfere with each other, apply the principle of superposition.

Sample Problem 1

The two waveforms shown in **Figure 6** are about to interfere with each other. Draw the resultant waveform.

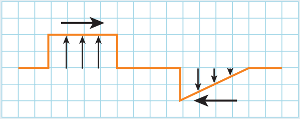


Figure 6

Step 1. On graph paper, draw the two waveforms, exactly as shown in Figure 6, but with one over the other. To draw the resultant waveform, use the point at which the midpoint of the waveform on the left coincides with the midpoint of the waveform on the right (**Figure 7**). Include the arrows showing the amplitudes above and below the equilibrium position.

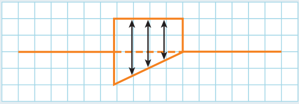


Figure 7

Step 2. For each segment of the graph paper, add the amplitudes of the top and the bottom waveforms. Use negative numbers for the bottom waveform. Draw the resultant waveform (**Figure 8**).

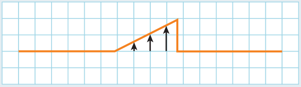


Figure 8

Step 3. Draw the waveforms moving away from each other, with the same characteristics they started with (**Figure 9**).

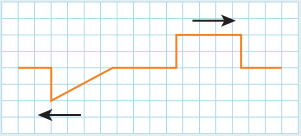


Figure 9

Practice

1. The two waveforms in **Figure 10** are about to interfere with each other. Draw the resultant waveform. K/U T/I

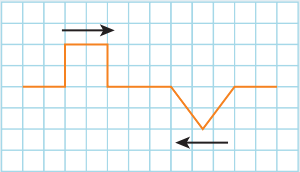


Figure 10

2. The two waveforms in **Figure 11** are about to interfere with each other. Draw the resultant waveform. K/U T/I

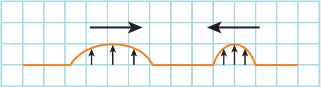


Figure 11

9.1 Summary

- The process of generating a new wave when two or more waves meet is called interference.
- Vibrating particles in a medium react to the sum of all forces on them. Their motion is caused by the sum total of forces on them.
- The principle of superposition states that, when two waves meet, the resulting amplitude is the sum of the individual amplitudes.
- Constructive interference occurs when two waves combine and the amplitude of the resulting wave is greater than the amplitudes of all the individual waves.
- Destructive interference occurs when two waves combine and the amplitude of the resulting wave is less than at least one of the original amplitudes.
- Humans can design technologies to take advantage of wave properties. An example of such a technology is noise-cancelling headphones.

UNIT TASK **BOOKMARK**

You can apply what you learned about interference to the device you construct for the Unit Task described on page 486.

9.1 Questions

1. Describe how waves combine. K/U
   (a) What happens when waves that are in phase combine?
   (b) What happens when waves that are out of phase combine?
2. Use the principle of superposition to determine the resulting waveform when the waves in **Figure 12** interfere with each other. T/I C

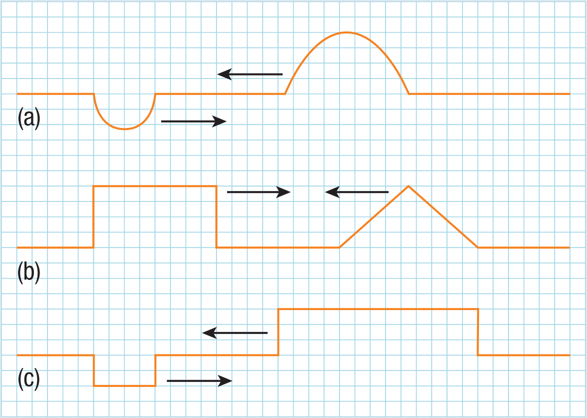


Figure 12

3. Study **Figure 13**. K/U T/I C

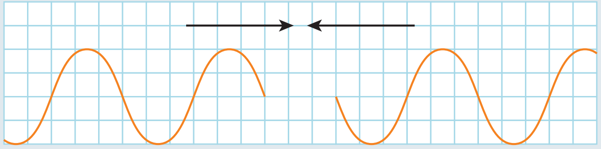


Figure 13

   (a) How would the pattern of the two waves coming together appear? Hint: Refer to Figure 5.
   (b) Make a sketch of what you would expect to see. Explain your thinking.
   (c) Assume that the continuous waves are out of phase by half a wavelength and are interfering. Make a sketch of what you would expect to see. Explain your thinking.

9.2 Waves at Media Boundaries

media boundary the location where two or more media meet

Figure 1 The walls and shapes of recording studios are carefully designed to ensure that the sound going to the microphone is a true representation of the work of the musician. The walls contain materials that absorb sound.

Recall from Chapter 8 that wave speed depends on some of the properties of the medium through which the wave is travelling. For example, the speed of sound in air depends on air temperature, and the speed of a wave along a rope depends on the density and tension of the rope. What happens if the medium changes? For example, what happens to a wave when it moves down a rope and encounters a different medium, such as air?

No medium is infinitely large, so all media have boundaries. The location where two media meet is called a **media boundary**. Media boundaries can take many forms. For example, they can be a change in the characteristics of a rope or the edge of a drumhead. A media boundary might also be the surface of the walls of a room where air and the wall material meet. Understanding how waves behave at media boundaries is useful. For instance, most schools have individual classrooms so that the discussion in one classroom does not interfere with the discussion next door. Musicians record their music in soundproof rooms so that only their own sound is recorded (**Figure 1**). You will learn more about the effect of sound produced in enclosed or restricted spaces—acoustics—in Chapter 10.

To explore the behaviour of waves at media boundaries, we first examine what happens in two simple cases: free-end reflections and fixed-end reflections.

Free-End Reflections

free-end reflection a reflection that occurs at a media boundary where the second medium is less dense than the first medium; reflections have an amplitude with the same orientation as the original wave

Consider two media, say medium 1 and medium 2, and a wave travelling through medium 1 into medium 2. If medium 1 is denser than medium 2, then the wave will move faster in medium 1 than in medium 2. In this case, the wave moving toward the boundary will be reflected in the same orientation as the incoming wave and with the same amplitude as the incoming wave (**Figure 2**). This is called a **free-end reflection**. You can generate a free-end reflection yourself by snapping a towel. The movement of the free end of a flag attached to a flagpole is another example of a free-end reflection (**Figure 3**). The flag flutters in the wind, but at its free end the wave encounters the atmosphere. The speed of the wave in each medium is significantly different. In free-end reflections, the medium the wave has been travelling through ends abruptly, typically into the atmosphere. Since the atmosphere is less dense than most media, the end of the medium can move freely.

Figure 3 When the waves in the flag reach the right side, they will reflect back through the flag material.

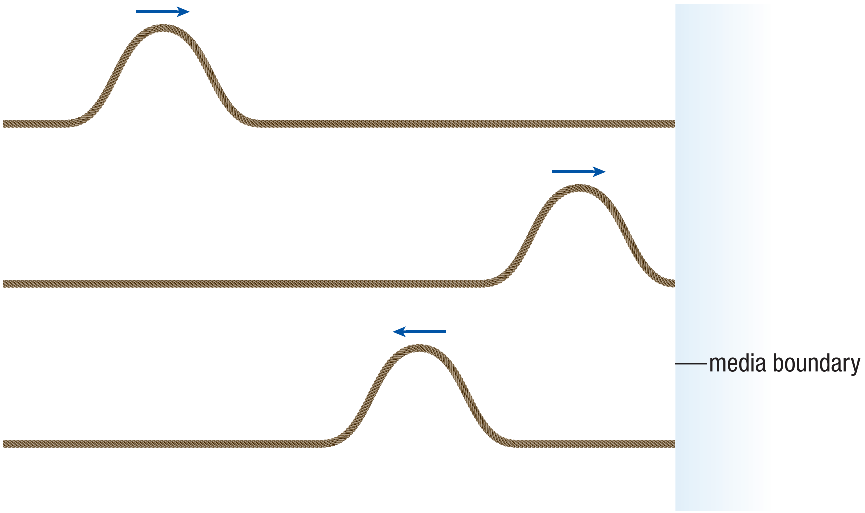


Figure 2 When a wave in one medium (for example, string) encounters a medium with a lower density (for example, air), the wave is reflected with the same orientation and amplitude as the original pulse.

As another example, suppose you are holding one end of a rope. If you send a pulse through the rope, the loose end moves freely. When the pulse encounters the end of the rope, it is reflected back to the source (Figure 2). Notice that the reflected wave from a free-end reflection is upright, and the characteristics of the pulse in the reflected waveform are identical to the characteristics of the original pulse. The wave does not continue to the right, beyond the media boundary. This is because the wave speed in the second medium is slower than the wave speed in the first medium.

Fixed-End Reflections

If a medium is fixed at one end, then when a wave reaches the media boundary a **fixed-end reflection** occurs. A fixed-end reflection also occurs when a medium is fixed at both ends, as in a harp (**Figure 4**).

Consider a pulse in a string moving toward a rigid, denser medium such as a wall (**Figure 5**). When the pulse reaches the fixed end, it is reflected. As you see in Figure 5, the reflected pulse has the same shape as the incoming pulse, but its orientation is inverted. We may explain this inversion as follows. When the pulse reaches the fixed end of the string, it exerts an upward force on the wall. In response, the wall exerts a downward force on the string in accordance with Newton's third law of motion. Therefore, the incoming upright pulse is inverted upon reflection.

fixed-end reflection a reflection that occurs at a media boundary where one end of the medium is unable to vibrate; reflections are inverted

Figure 4 A harp has strings anchored at both ends. When you pluck a harp string, you produce a wave. The wave moves back and forth along the string and encounters a fixed end at each end of the string.

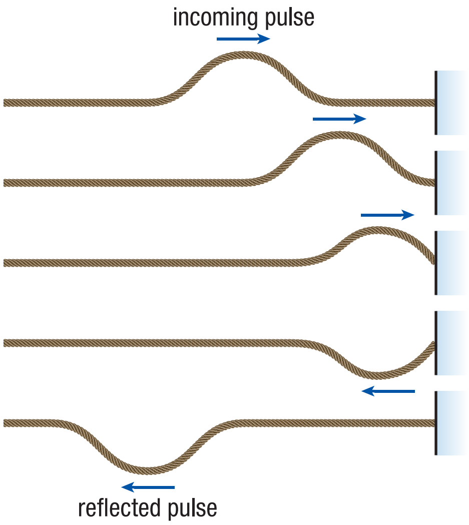


Figure 5 When a pulse in one medium meets a boundary with a denser medium, the reflected pulse is inverted.

The difference in the media as a wave reaches a media boundary may not be as dramatic as either the free-end or the fixed-end case. In nature there are media boundaries that are neither free-end nor fixed-end. For example, the boundary between water and air and the boundary between air and a tree are neither fixed-end boundaries nor free-end boundaries. If a wave travels from a medium in which its speed is faster to a medium in which its speed is slower, the wave can move more freely than it did in the faster medium.

transmission the motion of a wave through a medium, or motion of a wave from one medium to another medium

WEB LINK

To see an animation of reflection and transmission,

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Media Boundaries: Amplitudes

The amplitude of a wave before it encounters a media boundary is closely related to the wave's energy. The amplitude does not change if the wave's energy remains constant. When a wave encounters a media boundary that is not strictly an ideal free-end or fixed-end boundary, the wave splits into two. One wave is reflected, and the other is transmitted. The term **transmission** describes the process of a wave moving through a medium or moving from one medium into another medium. The amplitude of the original wave may not be shared equally by the reflected wave and the transmitted wave. However, the sum of the two amplitudes must equal the amplitude of the original wave (**Figure 6**).

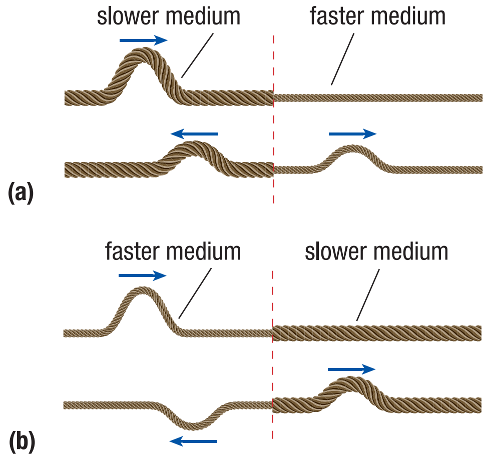

Figure 6 At a media boundary that is neither free-end nor fixed-end, the original wave splits into two waves. (a) If the wave moving along the rope encounters a medium that has a faster wave speed, then the wave splits into two, and one wave is reflected and the other is transmitted. The reflected wave is upright. (b) When a wave moves into a slower medium, then the wave splits into two, and one wave is reflected and the other is transmitted. The reflected wave is inverted.

If the difference between the wave speeds in the two media is small, transmission is preferred—the amplitude of the transmitted wave is closer to the amplitude of the original wave. As a result, the amplitude of the reflected wave is much smaller because of the conservation of energy. For cases in which the wave speed is significantly different between the two media, reflection is preferred—the amplitude of the reflected wave is closer to the amplitude of the original wave.

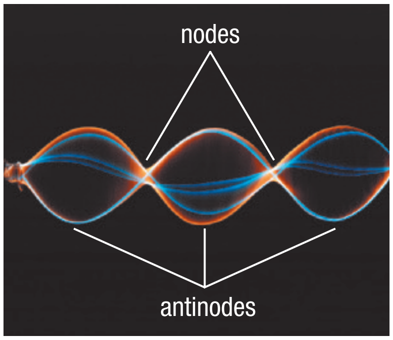

Figure 7 A standing wave pattern

standing wave an interference pattern produced when incoming and reflected waves interfere with each other; the effect is a wave pattern that appears to be stationary

node in a standing wave, the location where the particles of the medium are at rest

antinode in a standing wave, the location where the particles of the medium are moving with greatest speed; the amplitude will be twice the amplitude of the original wave

Investigation 9.2.1

Investigating Wave Speed on a String (p. 438)

In this investigation, you will investigate the wave speed of a standing wave.

Standing Waves

A special case of reflection at a media boundary is the production of standing waves. Suppose you send a series of waves at a certain frequency along a string of length L. The string is fixed at both ends. At the correct frequency, waves will reflect, and the reflected waves will superimpose on the stream of incoming waves to produce an interference pattern that makes the waves appear to be stationary. This interference pattern is called a **standing wave** and is shown in **Figure 7**.

In a standing wave there are locations where the particles of the medium do not move, called **nodes**. Standing waves also contain regions where the particles of the medium move with greatest speed. These regions are called **antinodes**.

The waves in a standing wave pattern interfere according to the principle of superposition. The waves are moving continuously. When the original wave is upright, so is the reflected wave from the previous crest. When the reflection has a trough, so does the original wave. At the antinodes, the amplitudes of the troughs and the crests are thus double that of the original wave.

The interference pattern appears to be stationary because it is produced by two otherwise identical waves travelling in opposite directions. The wave speed of a standing wave interference pattern is the difference between the wave speeds of the incoming and reflected waves. Since these are the same (direction is ignored), the wave speed of the standing wave is zero. However, remember that a standing wave is created by the interference of the incoming and reflected waves because these two waves are continuously moving.

WEB LINK

To see an animation of a standing wave,

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Standing Waves between Two Fixed Ends

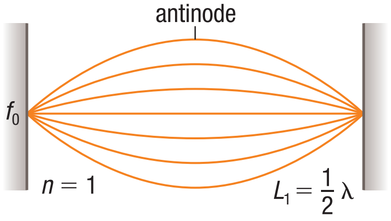
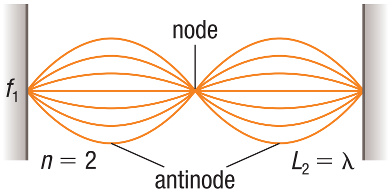
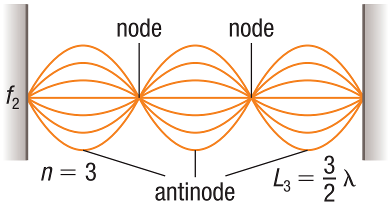
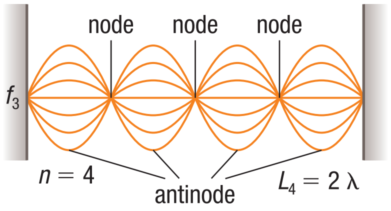
The properties of standing waves can be predicted mathematically. Consider a string with two fixed ends—it has a standing wave with nodes at both ends, as occurs when both ends are fixed (**Table 1**). In this case, the shortest length of the string, L, is equal to one half of the wavelength, $\lambda/2$, where λ is the wavelength. The frequency of the wave that produces the simplest standing wave is called the **fundamental frequency** (f_0) or the **first harmonic**. All standing waves after this require frequencies that are whole-number multiples of the fundamental frequency. These additional standing wave frequencies are called the nth harmonic of the fundamental frequency, where $n = 1$ for the fundamental frequency. **Harmonics** consist of the fundamental frequency (or first harmonic) of a musical sound as well as the frequencies that are whole-number multiples of the fundamental frequency. When a string, such as a violin string, vibrates with more than one frequency, the resulting sounds are called **overtones**. An overtone resulting from a string is very similar to the harmonic, except that the first overtone is equal to the second harmonic.

fundamental frequency or **first harmonic (f_0)** the lowest frequency that can produce a standing wave in a given medium

harmonics whole-number multiples of the fundamental frequency

overtone a sound resulting from a string that vibrates with more than one frequency

Table 1 Producing Standing Waves in a Medium with Fixed Ends

Symbol	Number of nodes between ends	Diagram	Harmonic (n)	Overtone
f_0	0		first	fundamental
f_1	1		second	first
f_2	2	 node node f_2 $n = 3$ antinode $L_3 = \frac{3}{2}\lambda$	third	second
f_3	3	 node node node f_3 $n = 4$ antinode $L_4 = 2\lambda$	fourth	third

Standing Waves between Free Ends and Fixed–Free Ends

Figure 10 A mute attached to the bell of a trumpet changes the sound.

Figure 8 shows standing waves in a medium with two free ends. Brass instruments, for example, have an open end for the musician to blow through and a bell at the other end for the music to come out of. **Figure 9** shows standing waves in a medium with a combination of free and fixed ends. An example of such a combination is a brass instrument using a mute, which is a device that fits over the end of the bell to change the sound the instrument makes (**Figure 10**).

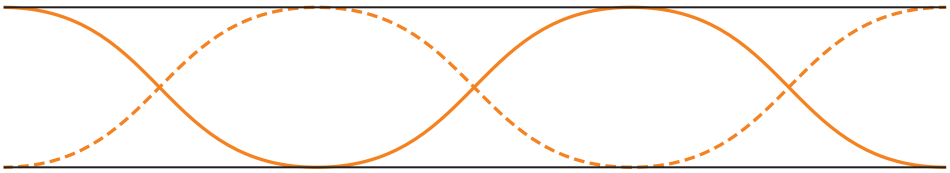


Figure 8 Standing waves can be generated in a medium with two open (free) ends. These types of standing waves are very common in brass instruments.

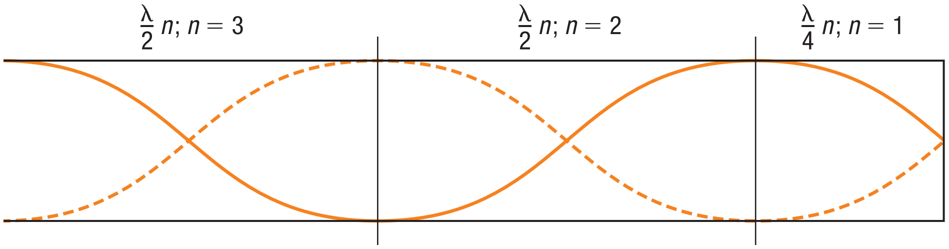

$\frac{\lambda}{2}n; n = 3$
$\frac{\lambda}{2}n; n = 2$
$\frac{\lambda}{4}n; n = 1$

Figure 9 A standing wave may be generated by having a source on one end, which is an antinode, and a node at the other end. Such standing waves can be created by a clarinet.

Calculations with Standing Waves

A brief inspection of the standing waves in Table 1 on page 423, Figure 8, and Figure 9 generated in media with two fixed ends or two free ends shows that the standing waves have the same mathematical properties. In general, the length of the medium, L, is equal to the number of the harmonic, n, times half the standing wave's wavelength, $\frac{\lambda}{2}$:

$$L_n = \frac{n\lambda}{2} \quad \text{for } n = 1, 2, 3, \ldots; \text{ media with fixed ends or free ends}$$

For media with a combination of fixed and free ends—a node at one end and an antinode at the other—the shortest possible length to produce a standing wave is $\frac{\lambda}{4}$ (see Figure 9). The next distance that produces a standing wave is $\frac{\lambda}{2}$ more than this, which is $\frac{3\lambda}{4}$. Therefore, the sequence of possible medium lengths to produce a standing wave in media with a free end and a fixed end is $\frac{\lambda}{4}, \frac{3\lambda}{4}, \frac{5\lambda}{4}$, and so on. The general equation for determining the length of the medium with an antinode at one end and a node at the other end is as follows:

$$L_n = \frac{(2n - 1)}{4}\lambda \quad \text{for } n = 1, 2, 3, \ldots; \text{ media with a fixed end and a free end}$$

We can use the mathematical relationships between the variables to predict what characteristics are required to produce standing waves. In Tutorial 1, we will demonstrate calculations using standing wave equations.

Tutorial 1 Standing Waves

Sample Problem 1

The speed of a wave on a string with a fixed end and a free end is 350 m/s. The frequency of the wave is 200.0 Hz. What length of string is necessary to produce a standing wave with the first harmonic?

Given: free and fixed ends; $v = 350$ m/s; $f = 200.0$ Hz; $n = 1$

Required: L_1

Analysis: We first determine the wavelength using the universal wave equation. We can then use the formula for fixed and free ends to calculate the required length.

$$\lambda = \frac{v}{f};\ L_n = \frac{(2n - 1)}{4}\lambda$$

Solution: Calculate the wavelength:

$$\begin{aligned}\lambda &= \frac{v}{f}\\ &= \frac{350\ \text{m/s}}{200.0\ \text{Hz}}\\ \lambda &= 1.75\ \text{m (one extra digit carried)}\end{aligned}$$

Calculate the length of string:

$$\begin{aligned}L_n &= \frac{(2n - 1)}{4}\lambda\\ L_1 &= \frac{1}{4}\lambda\\ &= \frac{1}{4}(1.75\ \text{m})\\ L_1 &= 0.44\ \text{m}\end{aligned}$$

Statement: A string that is 0.44 m long will produce a standing wave with the first harmonic.

Sample Problem 2

The sixth harmonic of a 65 cm guitar string is heard. If the speed of sound in the string is 206 m/s, what is the frequency of the standing wave?

Given: two fixed ends; $L_6 = 0.65$ m; $n = 6$; $v = 206$ m/s

Required: f_6

Analysis: First, we determine the wavelength of the guitar string using the relationship for fixed ends. Then we use the universal wave equation to calculate the frequency of the standing wave.

$$L_n = \frac{n\lambda}{2};\ v = f_6\lambda$$

Solution:

$$\begin{aligned}L_6 &= \frac{n\lambda}{2}\\ \lambda &= \frac{2L_6}{n}\\ &= \frac{(2)(0.65\ \text{m})}{6}\\ \lambda &= 0.2167\ \text{m (two extra digits carried)}\\ v &= f_6\lambda\\ f_6 &= \frac{v}{\lambda}\\ &= \frac{206\ \text{m/s}}{0.2167\ \text{m}}\\ f_6 &= 950\ \text{Hz}\end{aligned}$$

Statement: The frequency of the standing wave is 950 Hz.

Practice

1. A 0.44 m length of rope has one fixed end and one free end. A wave moves along the rope at the speed 350 m/s with a frequency of 200.0 Hz at $n = 1$. T/I
   - (a) What is L_1 if the frequency is doubled? [ans: $L_1 = 0.22$ m]
   - (b) What is the length of the string if $n = 3$? [ans: 2.2 m]
   - (c) What is L_1 if the speed of the wave on the string is reduced to 200 m/s? [ans: 0.25 m]
2. The speed of a wave travelling along a 0.65 m guitar string is 206 m/s. At $n = 6$, the frequency is 950 Hz. T/I
   - (a) What is the frequency if a string with a wave speed of 150 m/s is used? [ans: 690 Hz]
   - (b) What is the frequency if the string is tightened to make the wave speed 350 m/s? [ans: 1600 Hz]
3. A string fixed at both ends has a length of 1 m. With a frequency of 44 kHz (fourth overtone), standing waves are produced. Which harmonics will be audible to a human? (The frequency range for human hearing is 20 Hz to 20 kHz.) T/I [ans: the first and second harmonics]

Mini **Investigation**

Creating Standing Waves

Skills: Predicting, Performing, Observing, Analyzing, Communicating

SKILLS HANDBOOK A2.1

In this activity, you will create standing waves using a skipping rope and then using a standing wave machine.

Equipment and Materials: standing wave machine; skipping rope or other rope with a diameter of approximately 1 cm and length of approximately 3 m to 4 m

Part A: Using a Skipping Rope

1. Hold one end of the skipping rope tightly, and have your partner hold the other end. Slowly oscillate the skipping rope while your partner keeps his or her hand still while still holding onto the rope.
2. Slowly increase the frequency until you reach f_0.
3. Try to double the frequency and produce f_1.

A. How did you know when you had reached f_0? K/U

B. Was the experience of moving the rope any different when the first harmonic was achieved? K/U

Part B: Using a Standing Wave Machine

4. Connect the standing wave machine to its electrical power supply or to a wave function generator.
5. Slowly increase the frequency of the function generator and generate as many harmonics as possible.

C. Using the characteristics of the standing wave machine provided by your teacher, predict f_0. T/I

D. Did the frequencies at which the standing waves were produced agree with your predictions in C? Explain. K/U

UNIT TASK **BOOKMARK**

As you work on the Unit Task on page 486, apply what you have learned about standing waves and musical instruments.

9.2 Summary

- The location where two different media meet is called a media boundary. At a media boundary, a wave is partly reflected and partly transmitted.
- Free-end reflections produce reflections with the same orientation as the original wave, and fixed-end reflections produce reflections that have the opposite orientation to the original wave.
- A standing wave is a special case of interference. The waves in a standing wave pattern interfere according to the principle of superposition.
- In cases where a standing wave is produced in a medium where the medium is fixed at both ends or open at both ends, the length of the medium is a whole-number multiple of $\frac{\lambda}{2}$, the first harmonic.
- In cases where a standing wave is produced in a medium where the medium is fixed at one end and open at the other end, the length of the medium is determined by $L_n = \frac{(2n - 1)}{4}\lambda$.

9.2 Questions

1. Define the following terms in your own words: K/U C
   (a) standing wave
   (b) fundamental frequency
   (c) node
   (d) harmonics
2. Identify from your own experience an example of a wave that encounters a media boundary. A
   (a) From your observations, is the amplitude of the reflected wave or transmitted wave increased?
   (b) Does the change in the medium support your answer to (a)? Explain.
3. Describe from your own experience an example of a free-end reflection and a fixed-end reflection. A
4. Describe the conditions required to form a standing wave. K/U
5. A string is 2.4 m long, and the speed of sound along this string is 450 m/s. Calculate the frequency of the wave that would produce a first harmonic. Assume the string has nodes at both ends. K/U
6. You have an open air column of length 1.2 m in air at 20 °C. Calculate the frequency of the second harmonic. (Hint: An open air column has an antinode at both ends.) T/I
7. The air temperature is 25 °C, and an air column carries a standing sound wave at a frequency of 340 Hz. What is the length of the air column, which is closed at one end, if you want to hear the third harmonic? K/U
8. Consider a standing wave that has two fixed ends. Sketch
   (a) the original wave without a reflection
   (b) the reflected wave, without the original but synchronized in time to the original
   (c) the superposition of these two waves K/U C

Beats

9.3

Have you ever been listening to music and found yourself tapping your foot to the rhythm, or beat, of the music? This type of beat is a rhythmic beat. In physics, there is another kind of beat called an acoustical beat. An acoustical **beat** is a periodic change in sound intensity caused by the interference between two nearly identical sound waves. Acoustical beats are formed when the frequencies of interfering waves are very close in value. You hear beats as a change in loudness, from soft to loud.

beat periodic change in sound intensity caused by the interference between two nearly identical sound waves

WEB LINK

To see an animation and hear acoustical beats,

GO TO NELSON SCIENCE

The two waves in **Figure 1(a)** have similar frequencies. If the waves occur in the same medium at the same time, they will interfere with each other according to the principle of superposition and produce acoustical beats. **Figure 1(b)** shows the waves added together according to the principle of superposition. At times, the waves are in phase and constructive interference occurs. At other times, the waves move out of phase with each other and destructive interference occurs. As time passes, the waves move out of phase, then into phase again, and so on. As a result, a listener at some location within the medium hears a change in loudness, which is the beat. The amplitude of a beat varies in a predictable way.

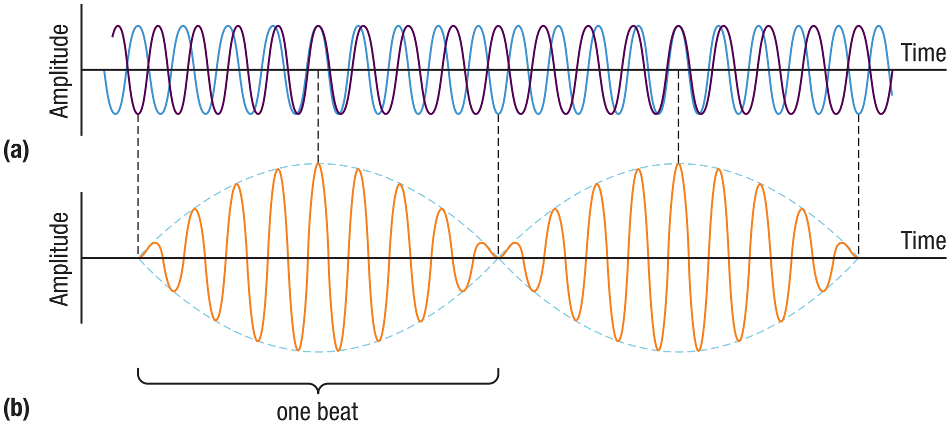


Figure 1 Beats are formed by the superposition of two waves with slightly different frequencies. (a) The individual sound waves are heard by an observer at some location within the medium. (b) The combined wave has an amplitude (blue dashed line) that varies in a regular manner.

Beats can be used to assess very small differences in frequency between two waves, because you can hear the change in loudness. Violinists and other musicians can use beats to tune their instruments by matching the musical notes with a standard note, perhaps from a piano or an oboe. A musical note refers to the specific frequency produced by a musical instrument, such as a piano, or other musical device, such as a tuning fork (**Figure 2**). By checking the frequency of the beats, musicians can determine how well the instrument is tuned. For example, when a piano tuner strikes a tuning fork of a given frequency and at the same time plays a piano key that is supposed to produce a note with the same frequency, she can determine the beat frequency by ear. The **beat frequency** is the frequency of the beats produced by the interference of two waves with slightly different frequencies. It is equal to the difference in frequencies of the two interfering waves. In this example, the beat frequency is the difference between the frequency of the tuning fork and the frequency of the piano key. The piano tuner can then tune the string to the desired frequency by adjusting the tension until she no longer hears any beats.

Figure 2 Tuning forks are available in different frequencies. A light tap to one tine (prong) of the fork sets both tines vibrating at a particular frequency.

beat frequency the frequency of beats produced by the interference of two waves with slightly different frequencies; equal to the difference in the frequencies of the interfering waves

CAREER LINK

To learn more about becoming an instrument tuner,

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Mini **Investigation**

Wave Beat Demonstration

Skills: Performing, Communicating

A beat can be created by two waves whose ability to form beats is not immediately apparent. When a graph is displayed on a computer screen, the graphing program attempts to place a dot in a particular location. Across the screen there is a frequency at which the program attempts to place these dots. At the same time, the screen has a physical set of pixels appearing at a certain frequency across the screen. When the frequency of the plot and that of the screen get close, a beat pattern appears.

Equipment and Materials: computer with projection display or graphing calculator

1. Set up a graph on the screen using the equation $y = \sin 10x$.
2. Change the value of 10: start increasing the value and replot the graph each time until your graph appears similar to the graph shown in **Figure 3**.

A. Most of the beats you will see with a computer are typically multiple beats. What might be causing this? T/I

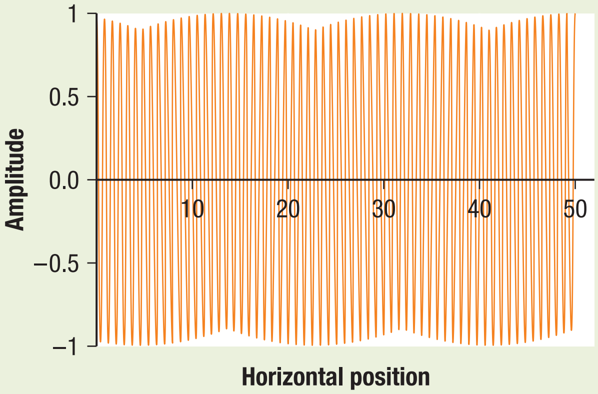

Figure 3

Mini **Investigation**

Creating Beats

Skills: Performing, Observing, Analyzing, Evaluating, Communicating

In this activity, you will produce audio beat patterns and view them on a computer.

Equipment and Materials: digital audio recording device, such as a personal music player or other device that produces audio computer files (for example, .wav or .mp3 type formats); digital audio editing software; pair of tuning forks that are close in frequency (about 5 Hz apart); rubber hammer; tuning fork whose frequency is about 40 Hz higher or lower than the frequency of one of the tuning forks in the pair; metre stick (optional)

1. Familiarize yourself with how to use the digital audio editing software.
2. Familiarize yourself with the operation of your recording device. Consider, for example, the controls, the distance at which the sensor can detect sound, and for how long it can record a sound.
3. Take the pair of tuning forks, and gently tap them with a rubber hammer, one at a time. Record their sounds.
4. With your partner holding both tuning forks, gently tap them both at the same time with a rubber hammer. Listen for the slow changes in the amplitude as the sound changes between loud and soft. After practising, record the sounds.
5. Gently tap one of the tuning forks from Step 4 and the third tuning fork at the same time. Record the sounds.
6. Upload the files into the software, and display them.
7. The waveforms of the recordings from Step 5 should appear smooth and cyclic, as in Figure 1. If they are not, it is possible that your tuning fork tap was a double tap and there were two or more waves vibrating on the tuning fork at the same time. Repeat your recordings of the pairs of tuning forks until the waveforms look similar to Figure 1.
8. Now display the beat pattern. Using the mouse or a metre stick on the projection screen, determine if the beat pattern is indeed a sum of the two closely spaced waveforms.
9. Display the waveform of the recording from Step 5. Check whether the waveform is still an addition of the two waveforms.

A. Do you think that the waveform produced in Step 5 is a beat? Explain your answer. T/I

B. Do you think the beat pattern would change if you tapped the pair of tuning forks at different times? Explain. K/U T/I

GO TO NELSON SCIENCE

Research This

Humming Fish

Skills: Researching, Communicating

The midshipman fish lives off the western coast of Canada and the United States (**Figure 4**). At mating time the males prepare nests and start humming to attract females to lay their eggs in the males' nests. The males then fertilize the eggs.

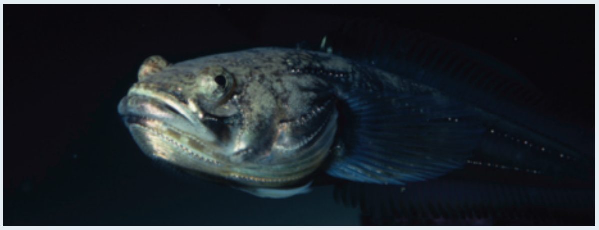

Figure 4 The midshipman fish

1. Research the midshipman fish using Internet sources.
2. Find out how the females choose which male will fertilize her eggs.

A. At approximately what frequency do the males hum? T/I

B. When all the males are humming, what does it sound like? T/I

C. How do the females choose which male will fertilize her eggs? Explain your answer. C A

GO TO NELSON SCIENCE

9.3 Summary

- Acoustical beats are an interference pattern formed by two waves with nearly identical frequencies.
- You can hear an acoustical beat as a periodic change in sound intensity.
- Many musical instruments can be tuned by a musician or an instrument tuner by listening to the beats generated between a standard note and that of their instrument.

9.3 Questions

1. Explain how beats are created. Refer to the principle of superposition. K/U
2. You are tuning a guitar by comparing the sound produced by the string with the sound produced by a standard tuning fork. You notice a beat frequency of 5 Hz when both sounds are present. As you tighten the guitar string, the beat frequency rises steadily to 8 Hz. In order to tune the string exactly to the tuning fork, should you continue to tighten the string or loosen the string? Explain your answer. K/U C
3. An airplane mechanic notices that the sound from an aircraft with two engines varies rapidly in loudness when both engines are running. What could be causing this variation from loud to soft? K/U
4. The two waveforms in **Figure 5** have the same amplitude but different frequencies. They are interfering with each other. Copy the two waveforms into your notebook, and draw the resulting beat pattern. Mark the points of constructive interference and destructive interference. K/U T/I C

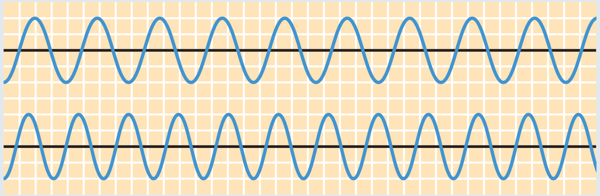

Figure 5

9.4

Damping and Resonance

damping a reduction in the amplitude of a wave as a result of energy absorption or destructive interference

If you push a child on a swing once, the child and swing will move back and forth. However, they will not move indefinitely. Eventually, the movement will slow down, and the child–swing system will come to rest at its equilibrium position. Friction between the child–swing system and air resistance reduce the energy in the child–swing system as time passes. The swing motion is said to be affected by **damping**. The air and the child–swing system absorb the energy provided by the push on the swing. We can observe absorption of wave energy by a medium as a reduction in the amplitude of the wave. **Figure 1** compares a waveform that has not been damped (Figure 1(a)) with a waveform that has been damped (Figure 1(b)). Destructive interference from many superimposed waveforms can also result in a reduction in the wave amplitude.

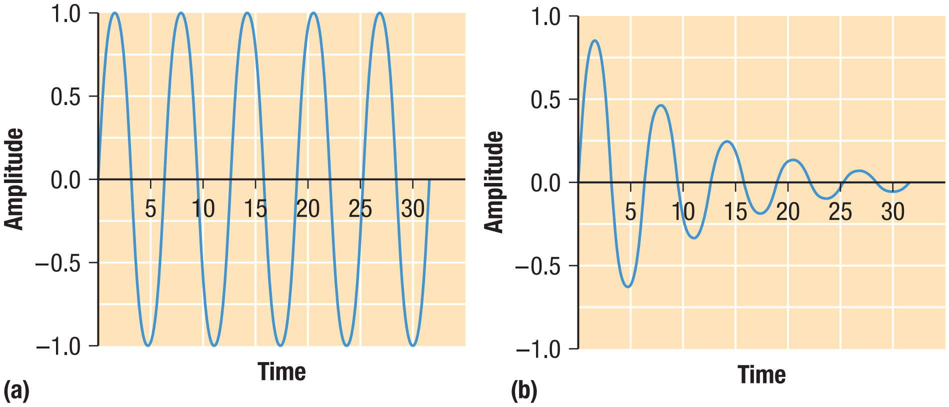

Figure 1 (a) Notice the consistent amplitude—this waveform is not being damped. (b) Notice how the amplitude decreases over time—this waveform is being damped. The amplitude will never increase unless energy is added to replace the energy that has been absorbed by the medium.

Resonance

resonant frequency the frequency at which a medium vibrates most easily

resonance the condition in which the frequency of a wave equals the resonant frequency of the wave's medium

All materials have frequencies at which they vibrate most easily. This is known as the system's **resonant frequency**. Consider the child–swing example. Suppose you keep the swing in motion by continuously pushing it with a certain frequency. To increase the amplitude of the swing motion, you must push the swing each time it returns to your hands. The amplitude can reach a maximum when the frequency of the pushing equals the natural frequency of the swing system, or the resonant frequency. Under these conditions, the child–swing system is said to be in **resonance**. If the energy put into the child–swing system per cycle of motion equals the energy lost as a result of friction, the amplitude remains constant. In other words, the damping effects are significantly reduced so that the amplitude can increase. An example of the dramatic increase in amplitude that can occur due to resonance is shown in **Figure 2**.

WEB **LINK**

To see a video demonstrating resonance,

GO TO NELSON SCIENCE

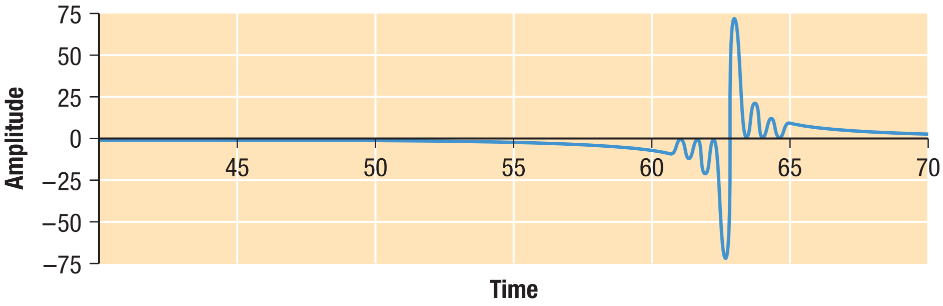

Figure 2 This waveform was generated by the interference of 100 waveforms. Over most of the graph the amplitude is so small that you cannot see it. However, when a resonant frequency is reached, the amplitude increases dramatically due to interference. Little energy is lost. Therefore, when the resonant conditions are met, significantly higher amplitudes are achieved. By adding 100 waves of frequencies that are fairly close, the waves combine to form a peak using constructive interference.

Resonance and Standing Waves

Recall from Section 9.2 that for a standing wave to occur, the wavelength (and frequency) of a wave must be a multiple of one of the harmonics. If the frequency of the wave is not a multiple of one of the harmonics, a pattern will appear that no longer has nodes, and the visible “standing” effect is lost, as shown in **Figure 3**. We often will see this as a reduction in amplitude. The real effect comes from losing the nodes so that the string shown in Figure 3 vibrates in changing locations, making it difficult to see.

Investigation **9.4.1**

Investigating Standing Waves in an Air Column (p. 439)

In this investigation, you will investigate standing waves as generated in an air column and find points of resonance.

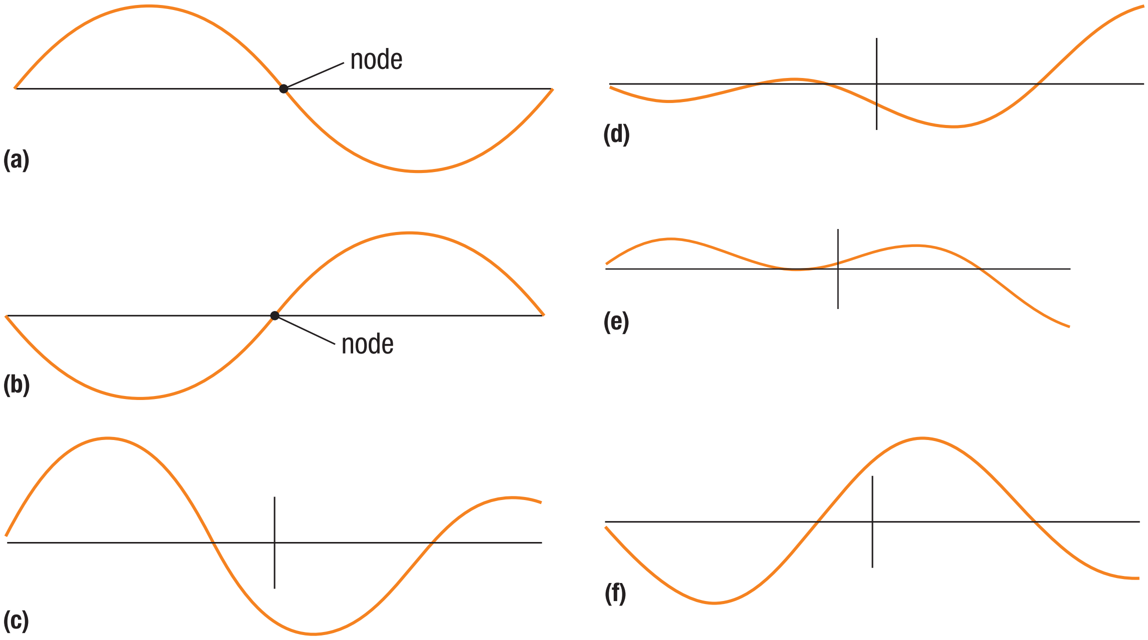

Figure 3 Parts (a) and (b) illustrate a typical $n = 2$ standing wave. Parts (c) to (f) illustrate the chaotic patterns that occur if the frequency is not at the correct value to set up a standing wave. Notice that in (a) and (b) the node shows no movement. In parts (c) through (f) there is no node.

Damping and Resonance in Vibrating Structures

Damping is sometimes desirable. You may want to reduce the effects of a vibration, so that sound will not carry from one room to the next, for example, or in a complicated structure such as a car or a building, where the effects of strong vibration can be dangerous.

In complicated structures such as a building, each component has its own resonant frequency and harmonics. When an external force, such as the wind, vibrates such a system at a frequency close to the structure’s resonant frequency, then resonance occurs. The amplitude of the vibration in the system increases significantly, perhaps to the point of damaging the building. For this reason, engineers are careful to avoid situations where resonance might occur within structures. They must carefully analyze structures to determine their resonant frequencies. While a building may not fall down as a result of such vibrations, other effects such as metal fatigue can occur that can damage the structure. Much experimentation is required to determine resonant frequencies of an entire structure. This phenomenon is called mechanical resonance and is described in more detail in Chapter 10.

CAREER **LINK**

To learn more about becoming a structural engineer,

GO TO NELSON SCIENCE

UNIT TASK BOOKMARK

As you work on the Unit Task on page 486, apply what you have learned about resonance to music and to structures and buildings.

9.4 Summary

- Damping is a condition in which the amplitude of a wave is reduced. Either the medium removes energy from a wave, or the effects of destructive interference reduce its amplitude.
- Damping due to destructive interference results in little energy loss. Given the right conditions, the amplitude can rapidly increase.
- All materials have frequencies at which they vibrate most easily, called the resonant frequency.
- Resonance is the condition in which the frequency of a system equals the wave medium’s resonant frequency or one of its harmonics. The wave’s amplitude can increase.
- Resonance is avoided in situations such as building construction where vibrations with large amplitudes are undesirable.

9.4 Questions

1. Define the following terms in your own words: K/U C
   (a) damping
   (b) resonant frequency
   (c) resonance
2. (a) Identify the two causes of damping.
   (b) Explain how damping occurs. K/U
3. If a mass–spring system is hung vertically and set into vibration, why does the motion eventually stop? K/U
4. All automobiles have shock absorbers. Research shock absorbers, and explain why they are used and how they work. 🌐 C A
5. Explain how standing waves are an example of resonance. K/U
6. Either through research or from your experience, identify two examples of damping that were not mentioned in this section. Explain why you think they are examples of damping. 🌐 K/U A
7. Either through research or from your own experience, identify two situations of resonance of a mechanical system (that is, no light, electronics, or magnetism). 🌐 K/U A
   (a) How do you know they are examples of resonance?
   (b) There will be a source of damping in each situation. Identify that source in each situation.
8. (a) Does resonance only occur when the amplitude is as high as can possibly be?
   (b) Given your answer in (a), would you expect more than one resonant frequency in a given situation? Explain. 🌐 K/U A

🌐 GO TO NELSON SCIENCE

The Doppler Effect

9.5

Have you ever noticed how the sound of an emergency vehicle's siren changes as it comes toward you and quickly changes to a lower sound after it passes by? The change in the characteristics of the sound are caused by changes in the frequency of the sound waves as the vehicle passes by. As the siren approaches you (the observer), the waves are compressed and the sound entering your ear is higher than the frequency of the sound originally emitted by the siren. As the vehicle passes you, the source is now moving away from you, so the effect is the opposite: the frequency of the sound detected by your ear is less than the frequency originally emitted by the siren (**Figure 1**). This phenomenon is called the **Doppler effect**. A simple situation is shown in **Figure 2**.

Doppler effect when a source of sound approaches an observer, the observed frequency of the sound increases; when the source moves away from an observer, the observed frequency of the sound decreases

WEB **LINK**

To see an animation of the Doppler effect,

GO TO NELSON SCIENCE

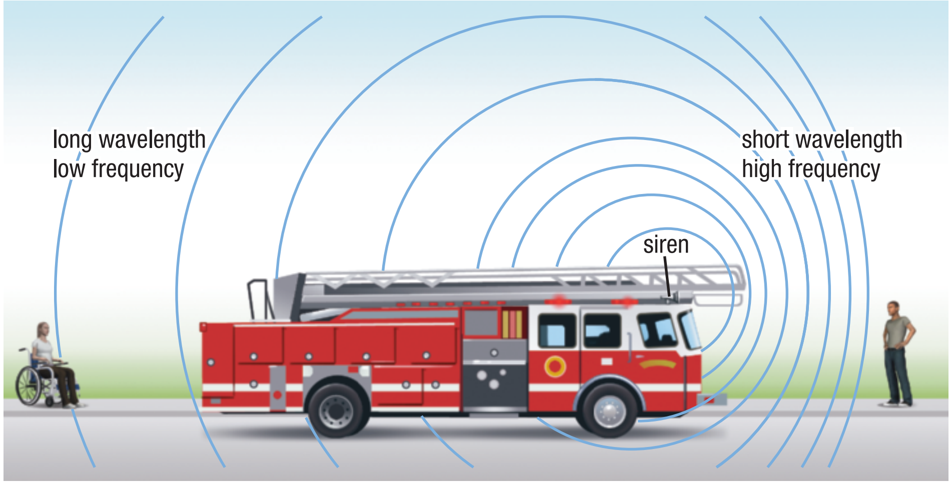

Figure 1 As the moving siren passes an observer, the observer hears a change in the siren's sound. The sound waves are compressed as the siren approaches the observer and more spread out as the siren passes the observer.

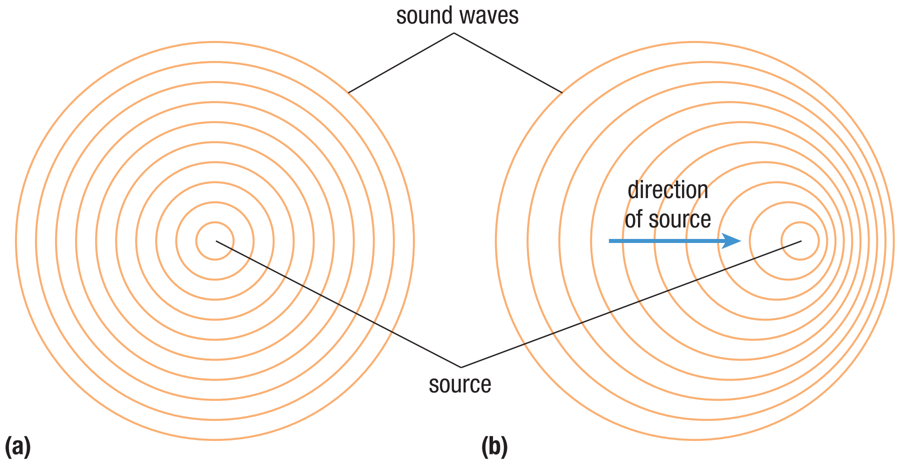

Figure 2 In (a), a stationary source emits sound with a particular frequency. In (b), the source is moving to the right. This motion has the effect of decreasing the distance between the crests of the sound waves in front of the source and increasing the crest-to-crest distance of the waves behind the moving source. A detector placed in front of the moving source will detect sound with a higher frequency, and a detector placed behind the moving source will detect sound with a lower frequency.

Not all moving sources of sound will generate a Doppler effect. The speed of the moving source must be a reasonable fraction of the speed of sound. The speed of sound is approximately 332 m/s. The speed of the siren on an emergency vehicle is approximately 30 m/s. So the vehicle speed is approximately 10 % of the speed of sound—a reasonable fraction. In addition, the moving source of sound has to have a component of its velocity vector moving parallel to the detector. So a sound source in a circular orbit around a detector, for instance, would not generate a Doppler effect.

Calculating the Doppler Effect

If either the detector or the source is moving (or both are moving), the frequency we observe, f_{obs}, and the frequency of the source, f_0, are related by the following formula:

$$f_{\text{obs}} = \left(\frac{v_{\text{sound}} + v_{\text{detector}}}{v_{\text{sound}} + v_{\text{source}}}\right) f_0$$

Note that in this text, we will only consider the case in which the source is moving and the detector is stationary. For example, a person standing at the corner of a street hears the siren of an ambulance speeding by. The speed of sound and the speed of the source are with respect to the medium, which is generally air.

When using the equation, if the source is moving toward the detector, the speed of the sound is considered to be negative. If the source is receding from the detector, the speed of the sound is considered to be positive.

A reasonable simplification is that the speeds of the source and the detector are said to be constant except for their signs, which instantly switch as the source passes the detector. In the following Tutorial we will calculate the change in frequency caused by the Doppler effect.

Tutorial 1 Calculating the Doppler Effect

Sample Problem 1

Suppose a fire truck is moving toward a stationary observer at 25.0 m/s. The frequency of the siren on the fire truck is 800.0 Hz. Calculate (a) the frequency detected by the observer as the fire truck approaches and (b) the frequency detected by the observer after the truck passes by. The speed of sound in this case is 342 m/s.

(a) **Given:** $v_{\text{detector}} = 0$; $v_{\text{source}} = -25.0$ m/s; $f_0 = 800.0$ Hz; $v_{\text{sound}} = 342$ m/s

Required: f_{obs}

Analysis: The fire truck is approaching the detector, so ensure that v_{source} is negative. The observer is stationary, so v_{detector} is zero. Use the equation to solve for the frequency detected by the observer, f_{obs}.

$$f_{\text{obs}} = \left(\frac{v_{\text{sound}} + v_{\text{detector}}}{v_{\text{sound}} + v_{\text{source}}}\right) f_0$$

Solution: $f_{\text{obs}} = \left(\frac{v_{\text{sound}} + v_{\text{detector}}}{v_{\text{sound}} + v_{\text{source}}}\right) f_0$

$$= \left(\frac{342\text{ m/s} + 0\text{ m/s}}{342\text{ m/s} + (-25.0\text{ m/s})}\right) 800.0\text{ Hz}$$

$$f_{\text{obs}} = 863\text{ Hz}$$

Statement: The detected frequency of the approaching fire truck's siren is 863 Hz.

(b) **Given:** $v_{\text{detector}} = 0$; $v_{\text{source}} = +25.0$ m/s; $f_0 = 800.0$ Hz; $v_{\text{sound}} = 342$ m/s

Required: f_{obs}

Analysis: When the fire truck is moving away after passing the observer, the frequency detected will change again. Since the source is now moving away, v_{source} is positive.

$$f_{\text{obs}} = \left(\frac{v_{\text{sound}} + v_{\text{detector}}}{v_{\text{sound}} + v_{\text{source}}}\right) f_0$$

Solution: $$f_{obs} = \left(\frac{v_{sound} + v_{detector}}{v_{sound} + v_{source}}\right)f_0$$

$$= \left(\frac{342\ \text{m/s} + 0\ \text{m/s}}{342\ \text{m/s} + (+25.0\ \text{m/s})}\right)800.0\ \text{Hz}$$

$$f_{obs} = 746\ \text{Hz}$$

Statement: The detected frequency of the receding fire truck's siren is 746 Hz.

Practice

1. A police car is approaching at a speed of 20.0 m/s with its siren emitting a frequency of 1.0 kHz. What frequency does a stationary observer detect? The speed of sound in this case is 330 m/s. T/I [ans: 1100 Hz]
2. An ambulance has just passed by your home. You detect that the frequency of the receding siren is 900.0 Hz. If you know that the frequency of the ambulance's siren is 950.0 Hz, how fast is the ambulance moving? The speed of sound in this case is 335 m/s. T/I [ans: 18.6 m/s]

9.5 Summary

- The frequency of a sound wave changes if the source and detector are in relative motion. This phenomenon is called the Doppler effect.
- When a source of sound approaches a stationary observer, the observed frequency increases. When the source moves away from a stationary observer, the observed frequency decreases.
- The formula used to calculate the change in frequencies detected by an observer as a result of the Doppler effect is

$$f_{obs} = \left(\frac{v_{sound} + v_{detector}}{v_{sound} + v_{source}}\right)f_0$$

- If the source is approaching the detector, the speed of the source is taken to be negative. If the source is receding from the detector, the speed of the source is taken to be positive.

UNIT TASK **BOOKMARK**

You can apply what you learned about the Doppler effect to the device you construct, or the technology you research, for the Unit Task described on page 486.

9.5 Questions

1. (a) Define the Doppler effect in your own words.
   (b) Give two examples of the Doppler effect from your experience that are not given in this section. K/U C A
2. Explain why a sound wave has a higher frequency when the source is approaching a stationary observer. K/U
3. A source emitting a sound at 300.0 Hz is moving toward an observer at 25 m/s. The air temperature is 15 °C. What is the frequency detected by the observer? K/U
4. A fire truck emitting a 450 Hz signal passes by a stationary detector. The difference in frequency measured by the detector is 58 Hz. If the speed of sound is 345 m/s, how fast is the fire truck moving? K/U
5. You are in a car moving at 90 km/h, and you see someone at the side of the highway. You use your horn to warn the person. The frequency of the horn is 440 Hz, and the air temperature is 0 °C. Calculate the frequency of the horn the person hears as you approach and as you pass. T/I
6. A source passing a stationary observer is emitting a frequency of 560 Hz. If the speed of sound is 345 m/s, what must the speed of the source be if the frequency source is 480 Hz? K/U T/I
7. Describe what happens to the frequency as a source of sound passes a stationary observer. Is this effect instantaneous? Explain. K/U

Rogue Waves

ABSTRACT

Accounts of monster (rogue) waves at sea that have sunk or nearly sunk large vessels have been common for centuries. Evidence includes waves big enough to capsize an ocean liner or an oil rig, or to bring down a hovering rescue helicopter. Scientific data, however, were lacking until 1995, when a North Sea oil rig recorded a wave almost 30 m high. More advanced technology such as remote buoys and satellites for monitoring sea conditions, coupled with modern technology onboard all ocean-going ships, has led scientists to estimate that as many as 400 rogue waves occur annually around the world. Rogue waves are a significant hazard to navigation and marine safety. Five candidate theories exist to explain the cause of rogue waves, but insufficient data have been collected to be sure. Due to the newly perceived hazard, significant research efforts are now being made to better understand this phenomenon.

Introduction

In December 1942, the RMS *Queen Mary* ocean liner, carrying 16 000 soldiers and crew, was 1100 km southwest of Scotland when it was hit by an enormous wave. The wave caused the ship to tilt more than 50°, but it slowly righted itself. It was later determined that if the ship had rolled even 5° farther, it would have capsized, leading to the deaths of most of the people on board.

This near tragedy was caused by a phenomenon that until recently was poorly understood: a rogue wave. A rogue wave is a wave or a series of waves that are 50 % to 100 % greater in height than typical for the given sea conditions. It is believed that the wave that struck the *Queen Mary* was at least 28 m high. Such waves had been rumoured in the past in reports by sailors who had survived such incidents. However, this time, the rogue wave had been witnessed by thousands.

Other rogue waves have been reported over the years:

- In 1978, the MS *München* was struck and sunk by a large wave. When the wreckage was inspected, heavy damage was found 20 m above the *München*'s waterline (the typical water height when the ship is afloat.)
- In 1985, a rogue wave 48 m high struck the Fastnet lighthouse in the United Kingdom (**Figure 1**). The wave was high enough to reach the light at the top.

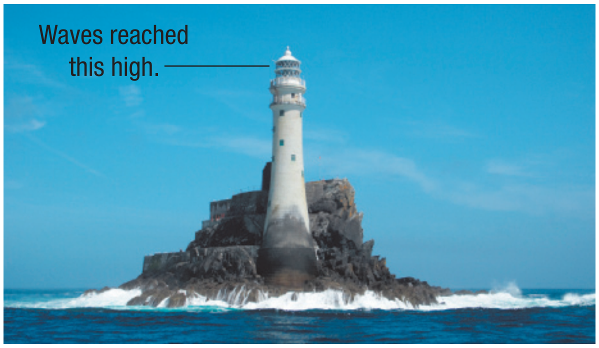

Figure 1 The lighthouse at Fastnet

- **Figure 2** shows the tanker *Overseas Chicago* interacting with a rogue wave in February 1993.

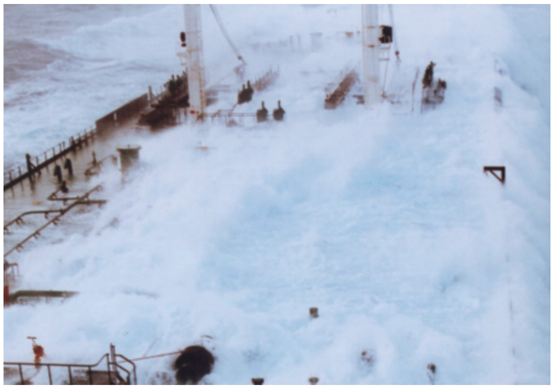

Figure 2 The *Overseas Chicago* was heading south from Valdez, Alaska, when a 20 m rogue wave struck it broadside.

- In 1995, the RMS *Queen Elizabeth 2* ocean liner was struck by a rogue wave at night. The captain said it came out of the darkness like the “white cliffs of Dover” and hit the ship 27 m above the waterline. He managed to “surf” the wave to prevent the ship from being overturned.

Formation of Rogue Waves

What causes these waves? Although the initial conditions that lead to rogue waves are still unknown, the ultimate cause of these waves is interference. There are thousands of waves in the ocean, all with different frequencies and wavelengths. They routinely pass through each other and very occasionally create a constructive interference pattern that produces a rogue wave or a series of successive waves. A rogue wave is *not* a tsunami. A tsunami is caused by a seismic event, typically an earthquake. Rogue waves, on the other hand, occur in rough weather or in regions where ocean currents are competing.

One process that may contribute to the formation of rogue waves is focusing due to the shape of the coastline or the seabed, which may direct waves to arrive at one place. A similar effect is created by large, strong currents, which can bring waves together (**Figure 3(a)**).

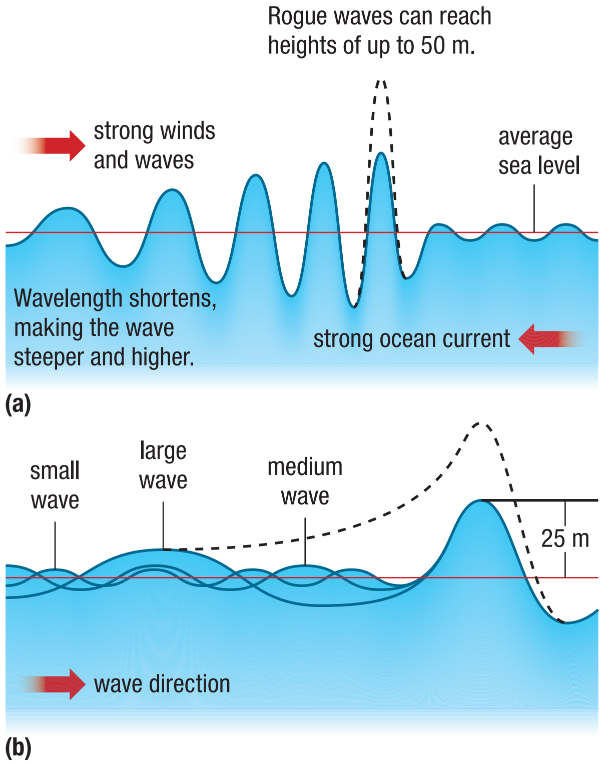

Figure 3 (a) A large and powerful current moving in the direction opposite to the direction of strong winds and waves can cause waves to combine to form a rogue wave. Notice the deep trough. (b) Different-sized waves moving at different speeds pass through one another. They can combine to form a rogue wave.

Computer modelling has shown that the steep crest of a rogue wave is preceded by a very deep trough. This model is consistent with the "hole in the sea" described by many mariners who have seen these waves. Longer-wavelength waves travel faster than shorter-wavelength waves, so in time the longer-wavelength waves catch up to the shorter waves ahead of them. This leads to constructive interference and a rogue wave (**Figure 3(b)**). The rogue effect is brief, though. When simulating this scenario, scientists are unable to explain the origin of this variable-wavelength wave train.

A ship that is affected by one of these waves is tested to its maximum. The wave is usually high enough to break over the bow. This causes tonnes of water to land on the deck and strike parts of the ship that cannot withstand these forces. The deep trough before the large crest puts the bow of the ship at the absolute minimum of the wave, making the crest even more devastating. Depending on the situation, a ship may actually drive itself underwater. When it runs into the deep trough, followed by the huge crest, the ship can be totally submerged. If the engine is still running, the propeller will drive it farther underwater. When the ship is underwater, it behaves more like a weightless object, but the propeller's action will cause the ship to flip over. It is then impossible for the ship to right itself.

Sightings of rogue waves have been claimed in many places, but are thought to be most common in the Bay of Biscay between England, France, and Spain; in the rapid currents off the north coast of the United Kingdom; and in the Southern Ocean, especially near the southern tips of South America and Africa. There is no real defence against such waves except to build a strong ship and to stay out of inclement weather.

Further Reading

Associated Press. (2010, March 4). Cruise passengers recall freak wave strike.

McGuinness Publishing. (2009). Death waves: Ship killers on the high seas.

Myers, D. (2010, June 18). What makes the giant freak wave "stable."

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9.6 Questions

1. What is a rogue wave? K/U
2. What is the ultimate cause of rogue waves? K/U
3. How are rogue waves able to destroy large ships? K/U
4. Research the candidate theories that explain the formation of rogue waves. Choose one theory, and write an abstract for a paper that explains the theory. K/U TI C
5. Rogue waves are not restricted to the open ocean. Research the wreck of the lake freighter SS *Edmund Fitzgerald*, which in 1975 sank in a violent storm on Lake Superior. Summarize your findings in one or two paragraphs. K/U C

CHAPTER 9 Investigations

Investigation 9.2.1 OBSERVATIONAL STUDY

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Investigating Wave Speed on a String

As you learned in Section 8.4, the speed of a wave on a string depends on the tension in the string and its linear density. In this investigation, you will verify this principle using the phenomenon of standing waves. You will determine whether the speed of a wave on a string is accurately described by the equation $v = \sqrt{\frac{F_T}{\mu}}$.

Equipment and Materials

- precision balance
- oscillating plunger
- 50 g mass
- function generator

When unplugging the function generator, pull from the plug, not the cord.

- wires to connect the function generator to the plunger
- clamp
- string or length of elastic bands connected together, 2 to 3 m long
- metre stick or measuring tape
- pulley
- apparatus to use as a bridge for the string

Procedure

1. Place the string on a precision balance, and measure its mass. Measure the length of the string, and calculate the linear density of the string.
2. Given the range of frequencies available to the plunger and a desire to observe at least the fourth harmonic, decide the string length and tension to use.
3. Attach the string to the plunger mechanism. Ensure that it is rigidly attached so that it cannot slip.
4. Secure the plunger in position with its own clamps or general clamps (**Figure 1**). Ensure that the clamping process does not affect the motion of the plunger.
5. Extend the string and attach the 50 g mass as shown in Figure 1.
6. Clamp the string in place at the desired length.
7. Start the plunger and set it at the frequency to produce a standing wave. Make fine adjustments to the frequency to ensure that a standing wave forms.

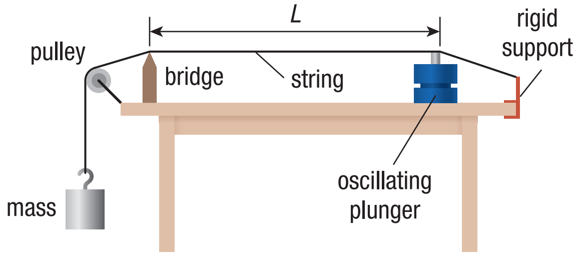


Figure 1

8. Repeat Steps 5 to 7 for at least ten frequency, length, and tension combinations. Record your measurements: the string's tension, the various vibrating string lengths, the various harmonics you observed, and the various frequency settings you used.

Analyze and Evaluate

SKILLS HANDBOOK A6.5

(a) Use your data to plot $\sqrt{F_T}$ versus v on a graph, and show a line of best fit. Calculate the slope of the line. The slope of the line should be $\frac{1}{\sqrt{\mu}}$. Compare the value of the calculated slope with the expected value, and discuss the results among your group. T/I C

(b) Were the standing waves symmetrical, or did they have unusual features? If there were unusual features, what might have caused them? Explain. T/I

(c) Discuss any sources of error in this investigation. Suggest how the investigation could be improved. T/I

(d) What happened to the amplitude of the wave on the string when the frequency was being adjusted between harmonics? Compare this with the standing wave situation. Was energy lost? Explain. T/I

Apply and Extend

(e) On a musical instrument such as a guitar or violin, what adjustments are made during playing or tuning, and how would these compare with the setup in this investigation? A

Investigation 9.4.1 OBSERVATIONAL STUDY

Investigating Standing Waves in an Air Column

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

As you learned in Section 9.2, waves reflect off both fixed and open ends of a medium, be it a rope or an air column. In this investigation, you will use what you have learned to predict the length of the resonance tube that will support the first harmonic for several tuning forks. In addition, you will determine points of resonance and the local speed of sound.

You will strike a tuning fork of known frequency and place it at the end of a resonance tube. The plunger of the tube can be retracted to create various lengths. You will hear a louder sound when resonance has occurred.

You will calculate the wavelength of the fundamental frequency by measuring the tube length for the harmonics you detect. The tuning fork is at the open end of the tube. Thus, the situation is for one open and one closed end. When you have produced a standing wave, the standing wave's amplitude should be about twice that of the tuning fork. As you modify the length, you will hear a variation in loudness. Using your wavelength measurements and the frequencies of the tuning forks, you will calculate the local speed of sound.

Purpose

To measure the length of the resonance tube that will support the first harmonic for various tuning forks and to measure the local speed of sound

Equipment and Materials

- resonance tube with plunger
- supports for the resonance tube that do not dampen the vibrations
- metre stick
- tuning forks of varying frequencies
- rubber hammer
- tape (optional)

Procedure

1. Set up the two stands for the resonance tube in an appropriate location. Allow extra space for the plunger's handle to extend past the end of the tube.
2. Place the tube on the supports and ensure that it is stable.
3. Insert the plunger and ensure that it is stable.
4. You may want to make some initial tape marks on the plunger's handle to indicate approximate distances.
5. Practise striking a tuning fork with a rubber hammer so that you do not double-strike it and that the volume is sufficient. Do *not* strike it too hard. If you bend the tuning fork, its properties will change.
6. With the plunger mostly retracted, strike a tuning fork and place it near the open end and listen. Now move the plunger steadily inward so that you get to the other end in about 1 s to 2 s. Listen for changing sound levels. Repeat this step two or three times until you are comfortable with the procedure.
7. Move the plunger in as far as possible. Determine the distance expected for $\frac{\lambda}{4}$ of the fundamental frequency. Use the frequency stamped on the tuning fork and an estimate of the speed of sound in air in your classroom. Retract your plunger slightly, so that it is still inside the expected $\frac{\lambda}{4}$.
8. Strike the tuning fork and slowly retract the plunger. Mark the location of the resonance point.
9. Repeat Step 8 several times and calculate an average value.
10. Retract the plunger farther and determine the lengths of the harmonics. Calculate averages of these as well.
11. Repeat Steps 5 through 10 as necessary for the various frequencies of tuning forks available.

Analyze and Evaluate

(a) Was the prediction you made about the length of the resonance tube supported? Explain. K/U

(b) Make a drawing of the standing waves in your resonance tube for each harmonic you detected. Using shading to indicate regions of high and low pressure, make at least one diagram of longitudinal waves in one of the harmonics you detected. C

(c) How did you know that you found a point of resonance? Explain. K/U

(d) Calculate the speed of sound for all of your resonance points and tuning forks. Do the answers agree? T/I

(e) Identify any sources of error in this investigation. Suggest how the procedure could be improved. T/I

(f) Make appropriate notes about your procedure and how it has been improved by your group. Include your notes in your lab report. T/I C

Apply and Extend

(g) Using what you have learned in this investigation, explain the purpose of the small holes along the tube of some wind instruments, such as the flute, that the musician covers up with his or her fingers. A

CHAPTER 9 SUMMARY

Summary Questions

1. Create a study guide based on the points in the margin on page 414. For each point, create three or four sub-points that provide further information, relevant examples, explanatory diagrams, or general equations.

2. Look back at the Starting Points questions on page 414. Answer these questions using what you have learned in this chapter. Compare your latest answers with those that you wrote at the beginning of the chapter. Note how your answers have changed.

Vocabulary

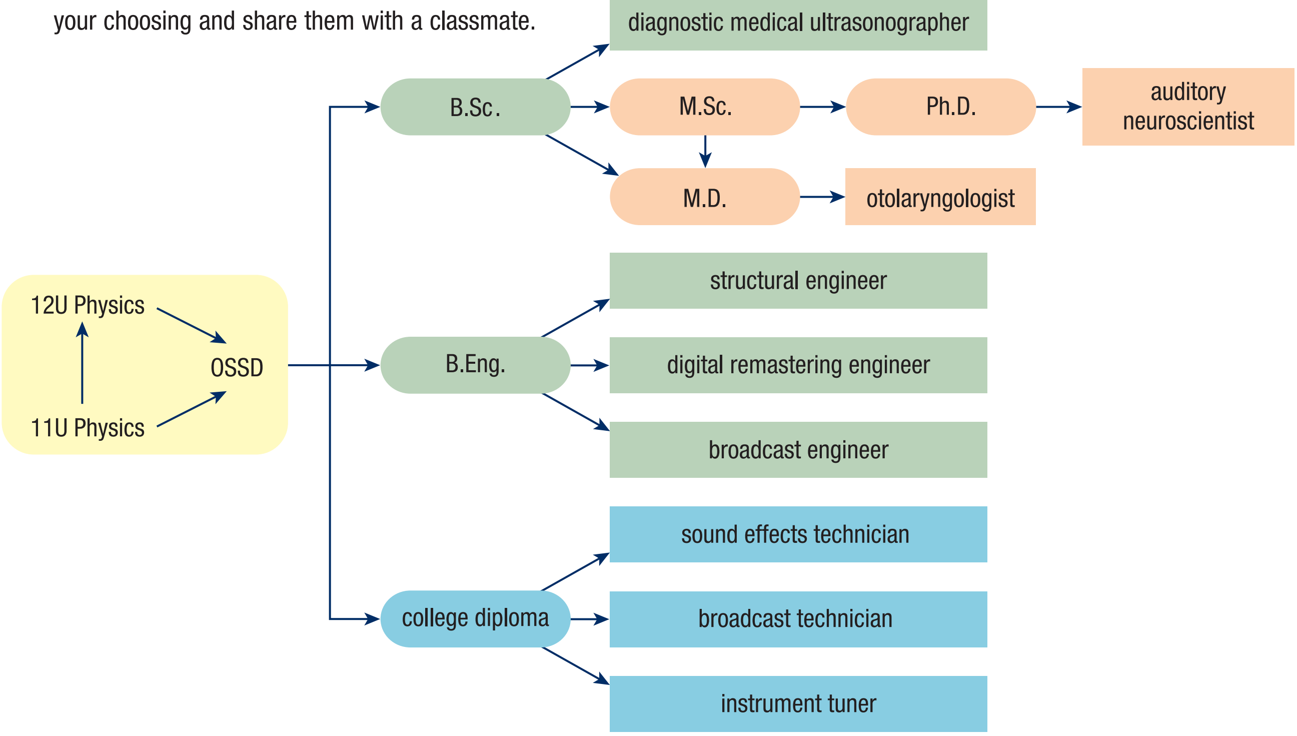
interference (p. 416)
principle of superposition (p. 416)
constructive interference (p. 416)
destructive interference (p. 416)
media boundary (p. 420)
free-end reflection (p. 420)
fixed-end reflection (p. 421)
transmission (p. 422)
standing wave (p. 422)
node (p. 422)
antinode (p. 422)
fundamental frequency or first harmonic (f_0) (p. 423)
harmonics (p. 423)
overtone (p. 423)
beat (p. 427)
beat frequency (p. 427)
damping (p. 430)
resonant frequency (p. 430)
resonance (p. 430)
Doppler effect (p. 433)

CAREER PATHWAYS

SKILLS HANDBOOK A7

Grade 11 Physics can lead to a wide range of careers. Some require a college diploma or a B.Sc. degree. Others require specialized or postgraduate degrees. This graphic organizer shows a few pathways to careers related to topics covered in this chapter.

1. Select an interesting career that relates to Wave Interactions. What is involved in pursuing this career? Research the educational requirements, post-secondary institutions offering the required programs, skill requirements, and potential employers. Summarize your findings in a format of your choosing and share them with a classmate.



12U Physics
11U Physics
OSSD
B.Sc.
diagnostic medical ultrasonographer
M.Sc.
Ph.D.
auditory neuroscientist
M.D.
otolaryngologist
B.Eng.
structural engineer
digital remastering engineer
broadcast engineer
college diploma
sound effects technician
broadcast technician
instrument tuner

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CHAPTER 9 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. The process of generating a waveform when two or more waves meet is called
   (a) conjoining
   (b) interdependence
   (c) superimposing
   (d) interference (9.1) K/U
2. The principle of superposition states that
   (a) the resulting amplitude of two interfering waves is the product of the individual amplitudes
   (b) the resulting amplitude of two interfering waves is the sum of the individual amplitudes
   (c) the resulting amplitude of two interfering waves is the difference of the individual amplitudes
   (d) the resulting amplitude of two interfering waves is the dividend of the individual amplitudes (9.1) K/U
3. If a wave travels from one medium into a different medium with a slower wave speed, then what type of vibration will the wave have at the end of the first medium? (9.2) K/U
   (a) no reflection
   (b) free-end reflection
   (c) fixed-end reflection
   (d) normal reflection
4. Which of the following is an example of a fixed-end reflection? (9.2) K/U
   (a) a flag blowing in the wind
   (b) the snapping of a towel
   (c) the vibration of a diving board
   (d) the vibration of guitar strings
5. The reflected wave from a fixed-end reflection is out of phase with the original wave by how much? (9.2) K/U
   (a) 0
   (b) a quarter wavelength
   (c) half a wavelength
   (d) a full wavelength
6. The frequency of a sound wave changes if the source and detector are in relative motion. What is this phenomenon called? (9.5) K/U
   (a) the principle of superposition
   (b) the Doppler effect
   (c) constructive interference
   (d) destructive interference
7. The siren on an emergency vehicle has a frequency of 840 Hz. The emergency vehicle passes you at a speed of 28 m/s. The frequency of the receding siren detected by you is
   (a) 780 Hz
   (b) 790 Hz
   (c) 810 Hz
   (d) 920 Hz (9.5) K/U
8. A rogue wave is produced from which wave interference pattern? (9.6) K/U
   (a) standing waves
   (b) beats
   (c) constructive interference
   (d) destructive interference

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

9. After two waves have passed through each other, the wavelength of each is decreased. (9.1) K/U
10. Destructive interference occurs when two or more waves combine to form a wave with a larger amplitude. (9.1) K/U
11. The location where two media meet is called a media boundary. (9.2) K/U
12. Transmission describes the motion of a wave through a medium, or the motion of a wave from one medium to another medium. (9.2) K/U
13. The locations that do not move in a standing wave are called antinodes. (9.2) K/U
14. An acoustical beat is a periodic change in sound intensity caused by the interference between two nearly identical sound waves. (9.3) K/U
15. Resonance is the reduction in the amplitude of a waveform caused by either energy absorption or destructive interference. (9.4) K/U
16. The resonant frequency of an object is the wavelength at which the object vibrates most naturally. (9.4) K/U
17. A component of the velocity vector of a moving source of sound must move parallel to the detector. (9.5) K/U

To do an online self-quiz,

GO TO NELSON SCIENCE

CHAPTER 9 REVIEW

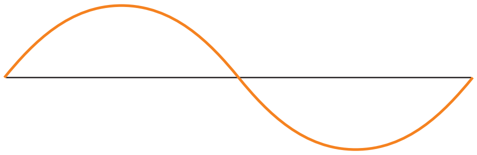
K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

Knowledge

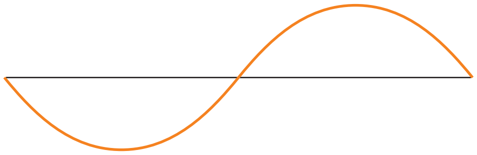
For each question, select the best answer from the four alternatives.

1. Two waves, with amplitudes 7.0 cm and 0.50 cm, approach each other on a string. What is the maximum amplitude of the string as they pass through each other? (9.1) K/U
   (a) 2.0 cm
   (b) 7.5 cm
   (c) 24 cm
   (d) 35 cm
2. Which of the following accurately describes waves? (9.1) K/U
   (a) Waves undergo perfectly inelastic collisions.
   (b) Waves bounce off one another without loss of energy.
   (c) Waves pass through each other without loss of energy.
   (d) All of the above are possible, depending on the initial conditions.
3. What is the typical particle motion in an ocean wave? (9.1) K/U
   (a) longitudinal
   (b) oval
   (c) vertical
   (d) helical
4. When do waves interfere constructively? (9.1) K/U
   (a) when they are moving in the same direction
   (b) when they are moving at the same speed in opposite directions
   (c) when they are out of phase
   (d) when they are in phase
5. Which of the following illustrates resonance? (9.4) K/U
   (a) turning down the volume on a personal music player
   (b) the sound produced when blowing in a half-full pop bottle
   (c) singing off-key
   (d) a child's swing slowing down
6. Which of the illustrations below shows the effect of damping? (9.4) K/U

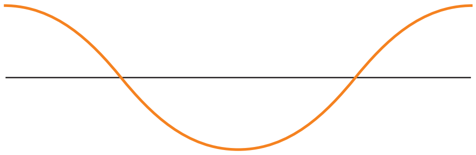
   (a)



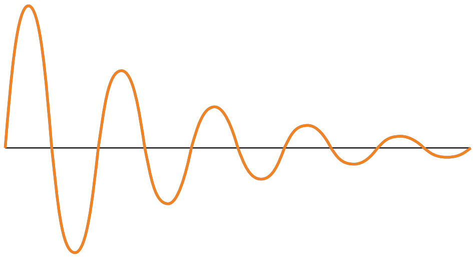
   (b)



   (c)



   (d)



7. Natural frequency is defined as the frequency at which
   (a) you can begin to hear sound
   (b) you can no longer hear sound
   (c) a beat is detected
   (d) an object vibrates most naturally (9.4) K/U
8. Which best describes the production of an acoustical beat? (9.3) K/U
   (a) sound patterns from a percussion instrument
   (b) interference of two sound waves with nearly identical frequencies
   (c) interference of two sound waves with very dissimilar frequencies
   (d) harmonic motion patterns

9. When tuning a guitar string with a tuning fork, you hear four beats. You tighten the string, repeat the tuning check, and hear two beats. What should you do next? (9.3) K/U
    (a) Tighten the string some more and repeat the tuning check.
    (b) Press the string at any point on the guitar's neck and repeat the tuning check.
    (c) Loosen the string and repeat the tuning check.
    (d) Choose another tuning fork with a different frequency and repeat the tuning check.
10. Which of the following may be the result of increased energy? (9.4) K/U
    (a) damping
    (b) longer wavelength
    (c) resonance
    (d) reduced amplitude
11. Which situation would produce a Doppler effect? (9.5) K/U
    (a) a fast train passing you with its horn on
    (b) a marching band passing you in a parade
    (c) a marching band approaching you in a parade
    (d) a sound source moving slowly in a circular path
12. Which of the following terms is used to describe the change in frequency of a sound wave when the sound source and detector are in relative motion? (9.5) K/U
    (a) sonar effect
    (b) radar effect
    (c) Doppler effect
    (d) beat effect
13. You are driving down the road and have to pull over because an ambulance is speeding toward you with its siren on. How does the frequency of the siren's sound compare to when you are stationary? (9.5) K/U
    (a) The frequency is higher than the frequency heard when you are stationary.
    (b) The frequency is lower than the frequency heard when you are stationary.
    (c) The frequency is the same.
    (d) You would not hear the siren while it is moving.
14. When stationary, the engine of a race car has a frequency of 1.3 kHz. When the race car passes a spectator in the stands at a speed of 55 m/s, what frequency does the spectator observe as the car drives away? Use 330 m/s as the speed of sound. (9.5) T/I
    (a) 1.0 kHz
    (b) 1.1 kHz
    (c) 1.2 kHz
    (d) 1.3 kHz
15. When an ocean wave appears twice as large as it should be and is not the result of seismic activity, it is called
    (a) a crest wave
    (b) a rolling wave
    (c) a random wave
    (d) a rogue wave (9.6) K/U

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

16. Interference leaves a wave permanently altered. (9.1) K/U
17. Halfway between two identical in-phase sound sources one would find a node. (9.2) K/U
18. A wave moving along a medium that is fixed at both ends reflects such that the reflected wave is inverted. (9.2) K/U
19. Transmission is preferred at a boundary between media in which the wave speeds are similar. (9.2) K/U
20. A pipe that is closed at one end resonates at a higher frequency than an identical pipe that is open at both ends. (9.2) K/U
21. If you pluck a violin string several times in a row and determine that the frequency remains the same, you have demonstrated the violin string's constant speed. (9.4) K/U
22. When you push a child's swing until it starts swinging on its own, you have found the swing's perpetual motion. (9.4) K/U
23. Each harmonic of a guitar string has the same frequency. (9.4) K/U
24. Resonance occurs when you vibrate something at its natural frequency. (9.4) K/U
25. Resonance occurs when you vibrate something at a multiple of its natural frequency. (9.4) K/U
26. A vibrating guitar string is an example of a standing wave. (9.4) K/U
27. If a cello instructor and her student play the same string on their cellos at the same time, two beats should be heard. (9.3) K/U
28. An antinode is the point of damping. (9.4) K/U
29. Rogue waves have been observed to reach heights of over 40 m. (9.6) K/U
30. Rogue waves are commonly preceded by a deep trough. (9.6) K/U

Match each term on the left with the most appropriate description on the right.

31.	(a) principle of superposition	(i)	the location where two media meet
	(b) standing wave	(ii)	a vibration resulting from a string that vibrates with more than one frequency
	(c) harmonics	(iii)	the resulting amplitude of two interfering waves is the sum of the amplitudes of the individual waves
	(d) media boundary	(iv)	an interference pattern resulting in the effect that the wave pattern appears to be stationary
	(e) overtone	(v)	whole-number multiples of f_0 (9.1, 9.2) K/U

Write a short answer to each question.

32. Classify the following musical instruments as free-end or fixed-end. (9.2) K/U
    (a) guitar
    (b) flute
    (c) organ pipe
    (d) piano
33. How does air temperature affect the tuning of an instrument that uses air columns, such as a trumpet? (9.2) A
34. If a wave is vibrating between harmonics, what does it look like? Explain your answer. (9.4) K/U
35. What role does superposition play in the creation of beats? (9.3) K/U
36. You are watching a parade, and a marching band passes you. Will the sound from the marching band exhibit a Doppler effect? Why or why not? (9.5) K/U

Understanding

37. A wave moves along a piece of yarn and then encounters a heavy rope (**Figure 1**). Describe the orientation of the transmitted and reflected waves. (9.2) K/U

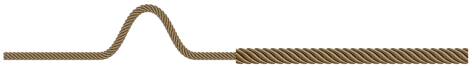


Figure 1

38. A clarinet is 60.0 cm long. Find the first three harmonic frequencies under the conditions below. Comment on whether the ambient temperature of a concert venue might affect the listener's experience. (9.2) T/I A
    (a) The air temperature is 15.0 °C.
    (b) The air temperature is 30.0 °C.
39. Becky and Rajiv are standing at different points in a long tunnel while Naomi adjusts her bass amplifier at one end. As Naomi plays an 88 Hz tone, Becky cannot hear much and Rajiv complains that the volume is too loud. What is the minimum distance between Becky and Rajiv? (Use 343 m/s for the speed of sound.) (9.2) T/I
40. A guitar player changes the notes produced by each string of his instrument by pressing down on the strings at specific locations on the guitar's neck. Explain the purpose of doing so in terms of standing waves. (9.2) K/U C
41. (a) In **Figure 2(b)**, how does the amplitude of the beat relate to the amplitude of the waves in **Figure 2(a)**?
    (b) Describe the pattern of sound represented in Figure 2(b). (9.3) K/U

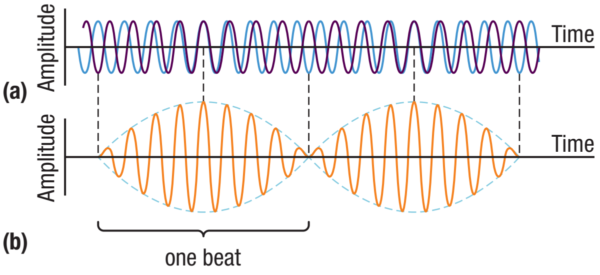


Figure 2

42. Explain the relationship between resonance and natural frequency. Give an example. (9.4) K/U
43. While researching the Doppler effect on the Internet, you find a drawing like the one in **Figure 3**. State what is incorrect and redraw the picture correctly. (9.5) K/U

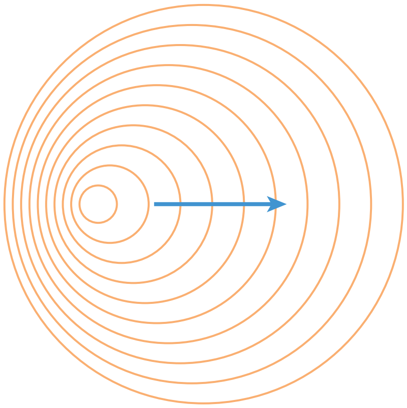


Figure 3

44. In the examples of the Doppler effect in Section 9.5, the observer was always stationary. Now consider cases in which the observer is in motion. **Figure 4** shows a stationary sound source and an observer in motion. For each case, describe how the frequency of the sound will vary from its source frequency from the point of view of the observer. (9.5) T/I

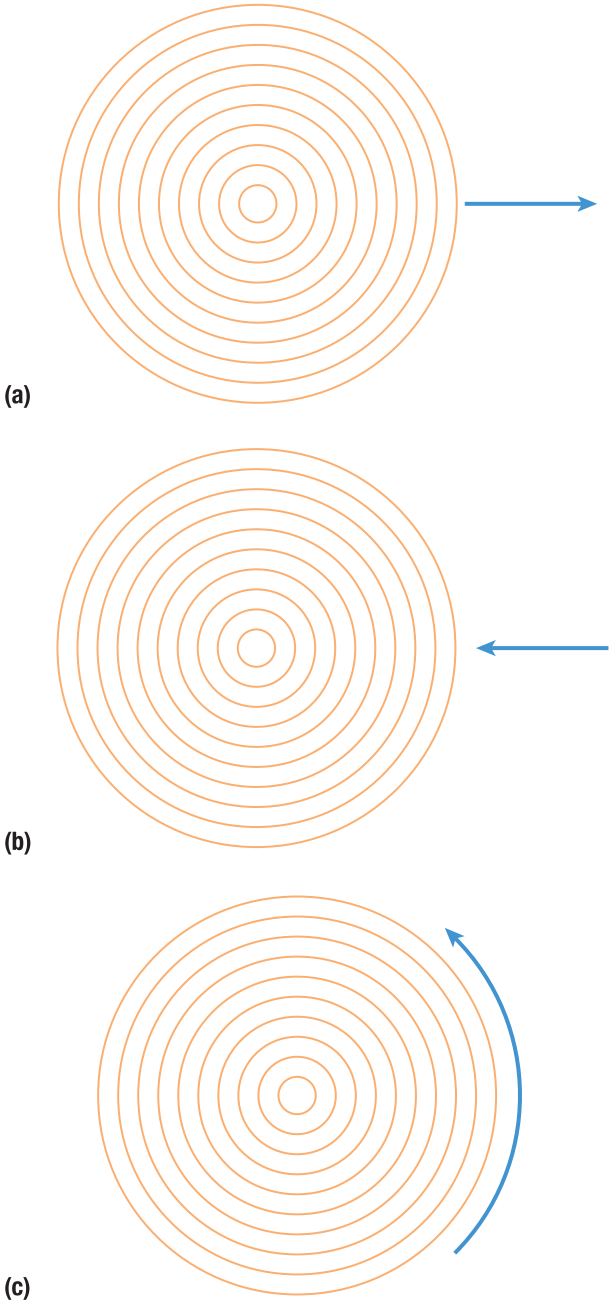


Figure 4

45. Stories of rogue waves have been around for centuries, but only recently have scientists been able to document and try to explain this phenomenon. In your own words, describe one of the theories on how rogue waves form. (9.6) K/U C

Analysis and Application

46. At sporting events, large crowds will sometimes participate in "the wave." Suppose that two groups on opposite ends of a stadium initiate the wave with one pulse moving to the right and the other moving to the left. Consider what happens when the two waves meet. (9.1, 9.2) K/U C
    (a) How is it similar to what happens with physical waves?
    (b) How does it differ?

47. **Figure 5** shows a rectangular wave pulse of amplitude 3 cm and length 6 cm encountering an inverted triangular pulse 2 cm deep and 6 cm long. Draw the shape of the interfering pulses at the instant when their centres coincide. (9.2) T/I

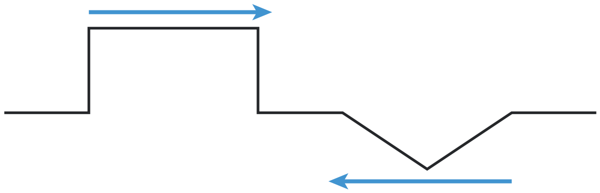


Figure 5

48. A rope 4.0 m long has a tension of 1240 N between fixed ends. The linear mass density of the rope is 1.9 kg/m. Calculate the first three harmonic frequencies of the rope. (9.2) T/I

49. A drum skin is stretched over one end of a pipe, creating a resonant air column with one open end and one fixed end. How long must the pipe be to achieve a resonant frequency of 280.0 Hz? (Use 343 m/s for the speed of sound.) (9.2) T/I

50. Suppose you have an empty 1 L pop container. You blow over the open end and listen to the sound that is produced. (9.2) T/I C
    (a) If you added some water to the container and repeated the procedure, how would the frequency that you hear change?
    (b) Explain why the frequency changes.

51. It is observed that a tube open at both ends exhibits harmonics at 438 Hz, 584 Hz, and 730 Hz. (9.2) T/I
    (a) Calculate the fundamental overtone of the tube.
    (b) Calculate the length of the tube. Assume the speed of sound is 343 m/s.

52. Suppose you and a friend attend a concert in which most of the sound comes from two main speakers mounted on either side of the stage (**Figure 6(a)**). Explain why you and your friend would have different experiences if the music consisted of a series of pure tones. A pure tone is a steady note without overtones, such as the waveform in **Figure 6(b)**. Explain why this phenomenon is not typically noticeable at actual events. (9.2) T/I A

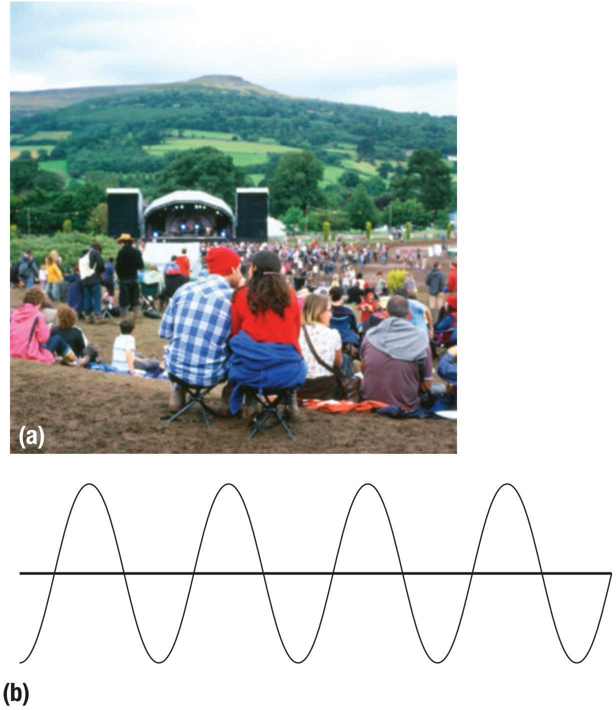


Figure 6

53. Suppose you have an air column that is closed at one end, but the closing device can be moved back and forth to change the length of the air column. You place a vibrating tuning fork (f = 330 Hz) at the open end of the column and set the length at one of the harmonics of this frequency. When listening to the tuning fork, how can you tell when you have produced a standing wave? (9.2) A

54. Set a graphing calculator in radian mode with the window xmin = 0, xmax = 10 or 20, ymin = −2, ymax = 2. (9.2, 9.3) T/I
    (a) Graph the equation $y_1 = \sin 6x$.
    (b) Graph the equation $y_2 = \sin 7x$.
    (c) Compare the amplitudes, nodes, and antinodes of y_1 and y_2.
    (d) Graph $y_3 = \sin 6x + \sin 7x$. Compare this graph's amplitudes, nodes, and antinodes to y_1 and y_2.
    (e) Does this illustrate the production of harmonics or beats? Explain your answer.

55. The two waveforms in **Figure 7** have the same amplitude but slightly different frequencies. They are in the same medium at the same time, and they are interfering with each other. Copy the two waveforms into your notebook, and draw the resulting beats. Use the principle of superposition, and mark the points of constructive interference and destructive interference. (9.3) T/I

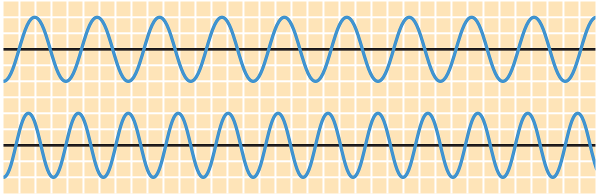


Figure 7

56. Compare damping techniques in terms of effective reduction of noise and vibration and in terms of environmental impact. Consider use of damping materials, isolation of vibrations, or other techniques you have learned about. (9.4) T/I

57. The long, slow moan that blue whales produce is commonly measured as 16.02 Hz. Suppose that a marine biologist is trying to measure this in a submarine that is approaching the whales at a speed of 50.0 m/s. The speed of sound in sea water is 1560 m/s. What is the frequency of sound observed by the marine biologist in the submarine? (9.5) T/I A

58. Pilots refer to their speeds in terms of the Mach number. When a jet reaches Mach speed, we hear a sonic boom. (9.5) T/I
    (a) Draw a sound wave diagram for the following scenario: a jet flying to the right at a speed slower than the speed of sound.
    (b) How does the distance between consecutive rings look on the right side of your diagram? What happens to this distance as the jet gets closer to the speed of sound? How would these rings look if the jet flew at exactly the speed of sound?
    (c) Draw the same diagram as in (a) but with the jet moving at the speed of sound.
    (d) Use your diagram from (c) and your knowledge of constructive interference to describe why a sonic boom is heard when a jet breaks the sound barrier.

Evaluation

59. A satellite emits radio waves at a constant frequency. These waves are picked up on the ground and made to beat against some standard frequency. The beat frequency is then sent through loudspeakers, and one "hears" the satellite signals. Predict how the sound changes as the satellite approaches, passes overhead, and recedes from the detector on the ground. (9.3) T/I
60. A glass of water is on a kitchen table. The floor of the room vibrates because of a laundry dryer in action. For certain speeds of rotation of the dryer, stationary ripples are observed on the surface of the water. Explain what is happening, and evaluate how effectively the energy from the vibration is transmitted. (9.4) T/I
61. Suppose that, in the Doppler effect for sound, the source and receiver are stationary, but the transmitting medium is moving with respect to the source and the receiver. Predict if there will be a change in frequency received. Explain your reasoning. (9.5) T/I

Reflect on Your Learning

62. How did your learning in Sections 9.3 and 9.4 connect to your knowledge from Sections 9.1 and 9.2? T/I
63. What was the most surprising thing you learned in Chapter 9? C
64. Explain an idea that you initially had difficulty with but gained an understanding of in Sections 9.3 and 9.4. T/I
65. How did the information you learned in this chapter affect your thinking about the dangers and benefits of vibrations and waves? T/I

Research

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66. Investigate the properties of different families of similar instruments (for example, violin versus cello, flute versus piccolo, trumpet versus trombone). Report on how the physics of standing waves applies in each family of instruments, and how the size of the instruments affects the quality of the sound produced. T/I C A
67. Some researchers are investigating the possibility of using the properties of waves to generate electricity. Research this idea. T/I
    (a) How do energy-conversion buoys use the properties of waves to generate electricity?
    (b) How much energy is possible using this method?
    (c) Researchers in Uppsala, Sweden, are experimenting with slow-moving waves to produce electricity. Describe how this technology works.
    (d) Approximately how much of Sweden's energy needs are expected to be met using slow-moving waves?
68. Some science-fiction authors have used the idea of interference between two speakers that emit hypersonic sound to create a voice that does not appear to have a source. T/I C A
    (a) Research hypersonic sound, and explain what it is.
    (b) Research the idea of using hypersonic sound as described above, and discuss the principles on which it would work. Report on the feasibility of such a concept coming into widespread use.
69. The Doppler effect was first explained in relation to sound waves. However, it can be observed in any moving object that emits or reflects waves; for example, the Doppler radar units used by the police to monitor traffic speeds (**Figure 8**). T/I

Figure 8

    (a) Research the Doppler effect.
    (b) Describe how Doppler radar works as used in police radar units.
    (c) Describe another application of the Doppler effect; for example, pertaining to weather or in baseball.
70. Rogue waves are thought to be most common in the Bay of Biscay between England, France, and Spain; off the north coast of the United Kingdom; and in the Southern Ocean, especially near the southern tips of South America and Africa. Choose one of these locations and research conditions such as wind direction. Hypothesize why rogue waves could be common in that location. K/U T/I

CHAPTER 10 Applications of Waves

KEY CONCEPTS

After completing this chapter you will be able to

- use scientific terminology related to mechanical and sound waves
- explain natural phenomena using the characteristics and properties of waves
- understand mechanical resonance and explain how mechanical resonance is used in a variety of situations
- analyze how properties of waves influence the design of buildings and structures
- explain the negative impact that waves can have on society and the environment, and assess technologies to reduce the impact

How Can an Understanding of Waves Be Applied to Music and Building Safety?

The concert hall on the facing page shows many ways that our understanding of sound waves is applied in a musical setting. While the seats are arranged to give everyone a clear view of the stage, the design has more purpose than you might think. To achieve the proper balance between the amount of sound reflected off the walls and other surfaces and the amount of sound absorbed, the design, construction, and placement of the seats, walls, ceiling, and floor are carefully considered. Even the wall coverings and the lighting are carefully chosen. The entire building is designed to improve the quality of the sound inside to maximize the experience for the audience.

Different musical instruments produce different sound waves as a result of their construction. Some instruments produce music through vibrating strings. Others use air columns, and still others use vibrating surfaces. Each instrument produces music based on the principles of resonance. In this chapter, you will learn how music is produced and how you hear sound.

In addition, you will learn how an understanding of waves can be applied to building structures like this concert hall, as well as bridges and skyscrapers. Such structures must be able to withstand earthquakes, which can cause wave motion that can damage the structure. However, earthquakes are not the only phenomena that can cause a large structure to sway back and forth. Wind is the main concern when constructing a large building in most locations. Under certain conditions the wind can cause large bridges and buildings to sway with great amplitudes, which can cause them to vibrate enough to injure people and even damage the structures. In rare circumstances, these buildings and bridges have been damaged enough by the wind that they have fallen.

STARTING **POINTS**

Answer the following questions using your current knowledge. You will have a chance to revisit these questions later, applying concepts and skills from the chapter.

1. What do you think is meant by "quality" of sound?
2. List three design features that you can see in the concert hall that might affect sound quality.
3. Why do you think the sound in a school gymnasium has a lower quality than the sound in a concert hall?
4. How do you detect sound?
5. Based on your experience, what is the difference between music and noise? How do you think scientists distinguish between music and noise?

Mini **Investigation**

Distinguishing between Music and Noise

Skills: Performing, Observing, Analyzing, Evaluating

SKILLS HANDBOOK A1.2

In this activity, you will produce sounds that most people would agree represent just noise and others would agree represent music. You will then use equipment to display the sound as a transverse wave and analyze the characteristics of each waveform.

If you use a hearing aid, tell your teacher. Ask to be excused from the room if you feel the noise or sound level is hurting you.

Equipment and Materials: microphone; amplifier; oscilloscope or computer; tuning fork; rubber hammer; stringed instrument; wind instrument; percussion instrument

1. Strike a tuning fork with a rubber hammer, and place it near the microphone. Adjust the oscilloscope until you see at least one wavelength of the sound produced on the display screen. In your notebook, sketch the waveform that you see on the display screen.
2. Repeat Step 1 while making what most people in the class agree is noise and not music. Yelling and scraping sounds are two ways to produce noise.
3. Repeat Step 2 using several musical instruments.

A. Describe several differences between the waves on the screen produced by noise and the waves produced by a musical instrument. T/I C

B. Some people define noise as anything that sounds annoying and music as something that sounds pleasant. What do you think of these definitions? Are these definitions specific enough for physics? C A

C. How do the waves produced by the instruments differ from the waves produced by the tuning fork? In your opinion, which produced a higher-quality sound, the tuning fork or the musical instruments? Explain your reasoning. C A

10.1 Human Hearing

You can hear very quiet sounds like a pin hitting the ground, but you can also hear very loud sounds, such as a jet taking off. In this section, you will learn about the human ear and how we hear sounds.

The Human Ear

The human ear can be viewed as a detector of sound—it captures the energy of sound waves. However, as you will see, the perception of sound has more to do with the brain than the ear.

If you ask people to point to and describe their ear, most will point to the external ear, or pinna, and describe it as a round, strange-looking part of the body with a lobe at the bottom. However, the pinna is only one part of the ear. The other parts are the middle ear and the inner ear (**Figure 1**).

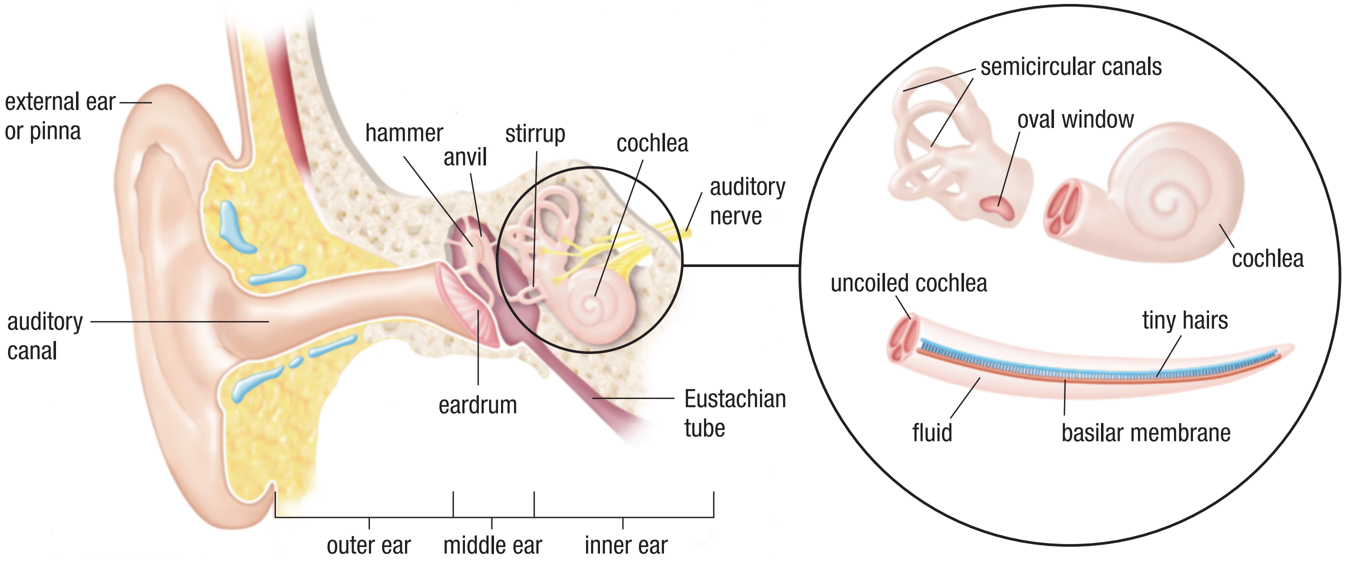

Figure 1 The parts of the human ear

The pinna acts like a funnel for sound. It directs, or channels, the sound waves into the auditory canal (also part of the external ear) toward the middle ear. The pinna is better equipped at channelling sound from a source in front of you than behind you. As you learned in Chapter 8, the audible hearing range of a healthy young adult is from 20 Hz to 20 kHz. However, the auditory canal magnifies sounds in the frequency range of 1000 Hz to 5500 Hz by a factor of about 10. As a result, most of the sound we perceive is in the frequency range of 1000 Hz to 5500 Hz.

The eardrum, or tympanic membrane, separates the outer ear from the middle ear. The eardrum is a tightly stretched, cone-shaped membrane that is thin but tough—it is less than 0.1 mm thick. It is also extremely sensitive—even the slightest vibrations can cause it to move. The eardrum is pulled inward by a muscle to keep it constantly taut.

The cavity containing the middle ear is filled with air and connected to the mouth by the Eustachian tube. The Eustachian tube only opens when you swallow or yawn. At these times, the air pressure inside the cavity will equalize with the air pressure outside. If the Eustachian tube becomes blocked (such as when you have a sinus cold), pressure equalization will not occur. As a result, pressure may build up inside the cavity, causing pain and loss of hearing.

Investigation **10.1.1**

Investigating Frequency, Loudness, and Human Hearing (p. 475)
In this investigation, you will test the range of human hearing in your class in terms of the range of frequency and loudness, as well as different areas in the school for loudness and hearing safety.

How You Hear

You learned in Chapter 8 that sound waves are longitudinal waves composed of alternating compressions and rarefactions in the air. When these alternating waves enter the auditory canal, they cause the eardrum to vibrate.

Recall that compressions are regions of higher atmospheric pressure. The higher pressure from a compression pushes the eardrum inward because the air particles that are pushed together exert an inward force on the eardrum (**Figure 2(a)**). Rarefactions are regions of lower atmospheric pressure, so the reverse effect occurs when rarefactions come in contact with the eardrum. The particles in the air are pulled away from the eardrum, which causes the eardrum to move outward due to the higher atmospheric pressure in the middle ear (**Figure 2(b)**). The resulting vibrations of the eardrum have the same frequency as the sound wave. If the amplitude of the sound wave increases, the eardrum may begin to vibrate with a greater amplitude.

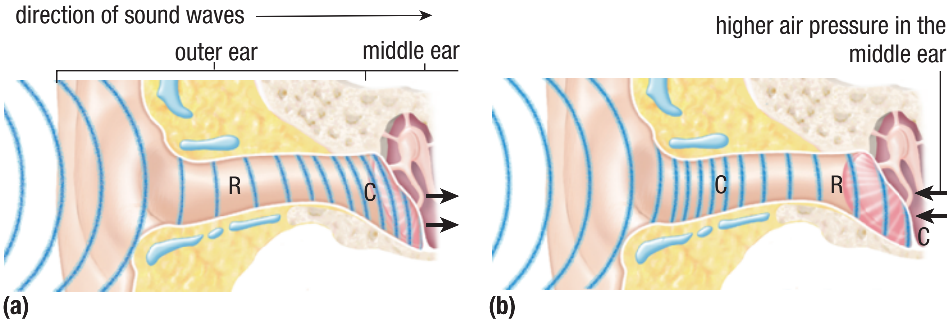

Figure 2 (a) Compressions push in the eardrum because of increased atmospheric pressure. (b) Rarefactions have the reverse effect by reducing pressure in the outer ear. The eardrum now pushes out because of the higher air pressure in the middle ear. The eardrum then starts to vibrate in response to the sound wave.

On the other side of the eardrum are the three smallest bones in the human body: the hammer (or malleus), the anvil (or incus), and the stirrup (or stapes). These bones are also shown in Figure 1 on page 450. The function of these bones is to transmit the vibrations of the eardrum to the inner ear while magnifying the pressure variations by a factor of about 22. The centre of the eardrum on the inner side is connected to the hammer. The hammer is a lever-like bone that rocks back and forth when the eardrum vibrates. The other end of the hammer is connected to the anvil, which is attached to the stirrup. When the hammer vibrates, it causes these other two bones to vibrate.

The stirrup transmits the eardrum vibrations to the start of the inner ear at the oval window, which is attached to the cochlea. When the eardrum is pushed in by a compression wave, the stirrup pushes inward on the oval window. When a rarefaction is present in the outer ear and the eardrum is pushed outward, the stirrup pulls the oval window outward.

The cochlea, a snail-shaped organ approximately 3 cm long, is divided into two sections by a partition called the basilar membrane (**Figure 3**). The vibrations at the oval window cause pressure waves in the fluid that fills the cochlea. Waves travel down one side of the cochlea, around the end of the partition, and back to the round window. These waves pass approximately 30 000 microscopic hair-like structures, each of which is attached to a single cell on the basilar membrane. These specialized structures are called hair cells. If the hairs on the hair cells start to vibrate, the mechanical energy of the hairs is converted into electrical energy in the cell, which in turn is transmitted to the brain by the auditory nerve. The basilar membrane responds to different frequencies along its length, with higher frequencies near the oval window and lower frequencies at the far end. When resonance is achieved, the membrane will vibrate in only one area, which then causes the hairs in that area to vibrate. The brain uses the number of vibrating hairs to determine the loudness of the sound and the location of the vibration to determine the frequency.

The inner ear also contains three hard, fluid-filled loops, called semicircular canals, at right angles to each other. These canals act like accelerometers that help maintain the body's balance by transmitting signals to the brain.

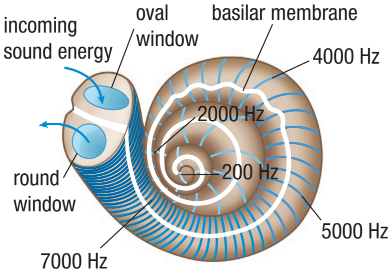

Figure 3 The basilar membrane responds to different frequencies at different locations.

Hearing Loss

Many of us take our hearing for granted, while others live with total or partial deafness. Moderately loud sounds will not usually damage the eardrum. Extremely loud sounds, such as explosions and volumes of music that are too loud for too long, however, can burst the eardrum. This damage can be repaired with surgery, but damage to the hairs in the cochlea cannot. A sudden burst of a very loud sound can rip away these hairs, as can a prolonged loud sound. Hair cells cannot be spontaneously regenerated in the human ear. Ear protection, however, can help reduce these effects. Employees in industries in which loud sounds are frequent or constant must wear ear protection. Many people with premature deafness have had prolonged exposure to loud sounds.

There is no cure for deafness when the signals from the cochlea are unable to travel through the auditory nerve. However, if hearing damage is related to problems in the eardrum or middle ear, then surgery or a hearing aid might improve hearing.

As illustrated in **Figure 4(a)**, hearing aids are often worn behind the ear or placed within the auditory canal. These aids magnify sounds and then direct them into the ear. A typical hearing aid consists of a microphone that picks up sounds, converts them to electrical signals, and sends them to an amplifier. The amplifier increases the amount of current in the electrical signal without changing the frequency and sends it to a speaker. The speaker changes the amplified electrical signal back into sound and sends it into the auditory canal. These types of hearing aids work best for mild to moderate hearing loss.

A cochlear implant (**Figure 4(b)**) works better for people with profound hearing loss because the implant bypasses the damaged parts of the ear. The implant converts sound into electrical signals and then sends the electrical signals directly to the auditory nerve. Other new types of hearing aids send vibrations directly to the bones in the middle ear or send vibrations through the skull directly to the cochlea.

CAREER **LINK**

Audiologists are trained to identify, treat, and prevent hearing loss.
To learn more about becoming an audiologist,

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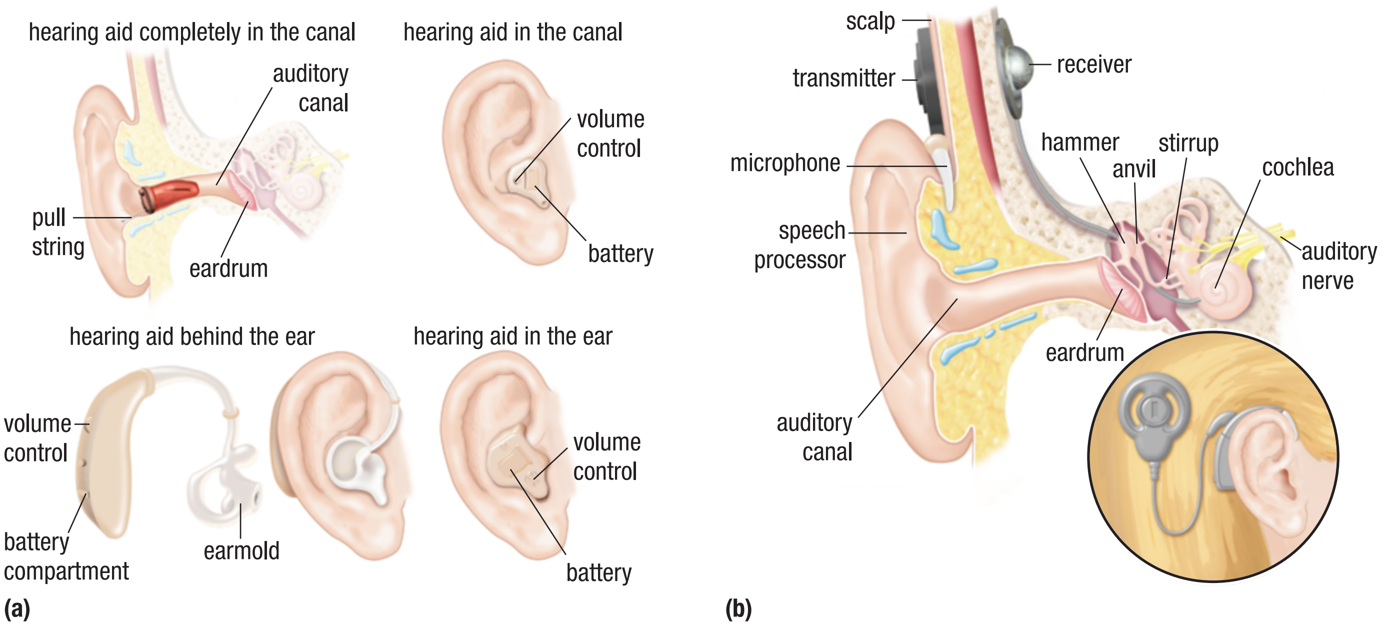
hearing aid completely in the canal
auditory canal
pull string
eardrum
hearing aid in the canal
volume control
battery
hearing aid behind the ear
volume control
battery compartment
earmold
hearing aid in the ear
volume control
battery
(a)
scalp
transmitter
receiver
microphone
hammer
anvil
stirrup
cochlea
speech processor
auditory nerve
eardrum
auditory canal
(b)

Figure 4 (a) Several different types of hearing aids (b) A cochlear implant

10.1 Summary

- The characteristics and properties of waves help explain natural phenomena, such as how we hear.
- The audible human hearing range is from 20 Hz to 20 kHz, but we perceive sound in the frequency range of 1000 Hz to 5500 Hz more than other frequencies.
- The outer ear consists of the pinna and auditory canal. The pinna gathers sound and channels it into the auditory canal toward the middle ear.
- The middle ear consists of the eardrum and three small bones: the hammer, the anvil, and the stirrup. The eardrum vibrates when it encounters sound waves, and the bones transmit and magnify the vibrations.
- The inner ear contains the cochlea and the auditory nerve. The vibrations are transformed into electrical impulses in the cochlea. The cochlea sends the impulses through the auditory nerve to the brain.
- Hearing aids can improve hearing loss in some cases.

UNIT TASK **BOOKMARK**

As you work on the Unit Task on page 486, apply what you have learned about how the human ear works. Will your constructed device produce sounds that could harm one's hearing?

10.1 Questions

1. Copy and complete **Table 1**. Include the following parts of the ear: pinna, auditory canal, eardrum, hammer, anvil, stirrup, Eustachian tube, cochlea, hair cells, auditory nerve, and semicircular canals. K/U C

Table 1 Parts of the Ear

Part of the ear	Location (outer, middle, or inner ear)	Description	Function
pinna			

2. **Figure 5** is a simple diagram that could be used to help younger students understand how the human ear works. K/U C

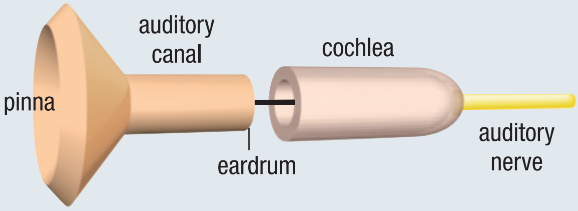

Figure 5 Schematic diagram of how the ear works

   (a) Write a paragraph that explains to a younger student how the human ear works. Refer to the diagram in your explanation.
   (b) In some ways the diagram is too simple. Explain.

3. Sometimes, when people go deep underwater, they experience severe pain in their ears due to the increased pressure of the water on the ear. Why do you think the extra pressure causes pain? What can be done to relieve the pain? K/U

4. What happens to the air pressure in an airplane that is increasing in altitude? Why should people avoid flying when they have a sinus infection or a sinus cold? K/U T/I A

5. Recently, scientists have grown new cochlear hair cells in mice. What implications might this have for hearing loss if scientists can eventually grow new hair cells in humans? A

6. Studies have shown that hearing loss increases with age, especially in people who are regularly exposed to loud noises. K/U
   (a) Give a reasonable explanation for why this happens.
   (b) What precautions should people take to avoid hearing loss as they get older?

7. Some animals, such as cats, can rotate their pinnae in different directions. Explain why this is an advantage for these animals over humans. A

8. Sometimes the eardrum can develop small perforations. In some cases, these perforations will heal naturally, just like the skin does when it receives a small cut. T/I A
   (a) What effect will these perforations have on hearing? Explain your reasoning.
   (b) Research these perforations in eardrums. Explain how the perforations can affect the middle ear if they persist, and how the perforations are repaired.

9. Research one type of hearing aid mentioned in this section. Determine the design, limitations, risks, and cost. A

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10.2 Musical Instruments

Music is composed of sounds, so understanding the physics of sound helps us understand music from a scientific perspective. It is important to understand music because music is an essential part of most cultures around the world, including Canadian culture. Many components go into making music: singers, songwriters, song recorders, musicians, and of course musical instruments. In this section, you will learn how musical instruments produce music.

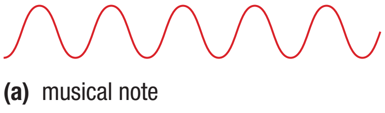
music sound that originates from a combination of musical notes that originate from a source that vibrates in a uniform manner with one or more constant frequencies

noise sound that originates from a source that vibrates in a random manner

Music and Musical Sounds

What some people call music others might call noise. To most people, noise is something that sounds unpleasant and annoying, while music is harmonious and pleasant. If we use these descriptions, we are forced to conclude that music and noise are a matter of opinion; that is, they are subjective. However, physicists need a more scientific definition for both music and noise.

A musical note originates from a source that vibrates in a uniform manner with one or more constant frequencies. **Music** is a combination of musical notes. A musical note looks like a constant waveform when displayed on an oscilloscope (**Figure 1(a)**). **Noise** originates from a source that vibrates in a non-uniform, random manner, and the waveform looks erratic in frequency and amplitude (**Figure 1(b)**).


(a) musical note

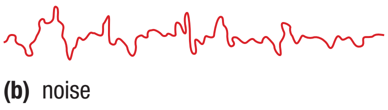

(b) noise

Figure 1 Sound traces on an oscilloscope: (a) a musical note (b) noise

Characteristics of Musical Sounds

Musical sounds have three main characteristics: loudness, pitch, and quality. These characteristics are subjective because they depend not only on the source but on the perception of the listener. Recall from Section 8.5 that greater amplitudes of vibration of air molecules mean louder sounds. However, the loudness a person hears depends on both the ear hearing the sound and the source of the sound. For example, a person who cannot detect a particular frequency will report no loudness, while someone who can hear the frequency may claim that the sound is very loud.

pitch the general perception of the highness or lowness of a sound; depends on the frequency, complexity, and loudness of the sound

The **pitch** of a sound is related to the frequency of the sound waves. Although there is an objective relationship between pitch and frequency, the pitch detected by a person depends on the observer, the complexity of the sound, and even the loudness. Generally speaking, a person will report a higher pitch when higher frequencies are produced by the source (**Figure 2**).

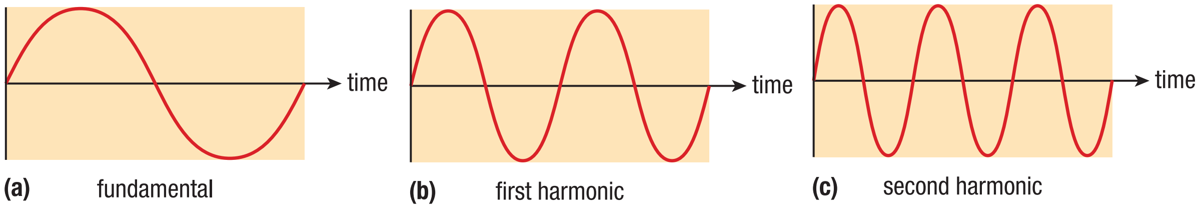


Figure 2 Higher frequencies have shorter wavelengths and produce higher pitches.

quality the pleasantness of a sound; related to the waveform of the sound

A tuning fork makes a simple musical note consisting of one frequency, but most musical instruments produce music composed of a fundamental frequency (f_0) as well as several harmonics ($2f_0$, $3f_0$, $4f_0$, . . .). The **quality** of a musical sound is the pleasantness of the sound. Sound quality depends on the number of harmonics, besides the fundamental frequency, and the intensity of these harmonics.

Musical Instruments

Musical instruments are grouped into three categories, depending on how they are used to produce vibrations (**Figure 3**).

- Stringed instruments: sound produced by plucking, striking, or bowing a string
- Wind instruments: sound produced via vibrating air molecules in columns
- Percussion instruments: sound produced by striking a surface

Figure 3 There is a large variety of musical instruments. They are grouped by how they produce sound.

Stringed Instruments

A string in a stringed instrument can be thought of as a tightly stretched spring fixed at both ends. Recall that strings can resonate with various frequencies, but the string must have a node at both ends. Increasing the tension in the string increases the fundamental frequency at which it will vibrate. Increasing the length, diameter, or tension of the string decreases the fundamental frequency. If the frequencies are high enough (20 Hz), the string can produce sounds audible to humans. This is how stringed instruments produce music.

Most stringed instruments, such as the guitar and piano, consist of a **resonator** (usually a case box or sounding board) and several strings (vibrator) fixed at each end under tension. A string alone produces very little sound, and the sound is often unpleasant. The resonator helps improve loudness and quality. The vibrations of the string are forced into the resonator, causing resonance. Even a tuning fork produces a louder and higher-quality sound when attached to a case box.

resonator an object, usually a hollow chamber called a case box or a sounding board, that vibrates in resonance with the source of sound

Stringed instruments that are usually played by plucking include the guitar, banjo, mandolin, ukulele, harpsichord, and some types of violin. If the string is plucked gently in the middle, a strong first harmonic is produced (**Figure 4(a)**). If the string is plucked one-quarter of its length from one fixed end, then other harmonics are produced and the quality of the sound changes (**Figure 4(b)**). In this case, the string vibrates with two simultaneous frequencies superimposed on each other. If the position where the string is plucked is even closer to the fixed end, the harmonics produced change again, resulting in a different quality of sound (**Figure 4(c)**).

Another common stringed instrument is the piano. The keys of a piano are connected to a series of levers. The levers cause a small hammer to strike a string (or strings) to make the string vibrate, thereby producing a musical note (**Figure 5**). The strings vary in length, thickness, and tension to enable them to produce different notes. The shorter, thinner, and higher-tension strings produce higher notes (up to 4186 Hz), and the longer, thicker, and lower-tension strings produce lower notes (as low as 27.5 Hz). The sounds from the strings are enhanced in loudness and quality by the wooden sounding board (resonator) of the piano.

Figure 5 When struck by the hammer, the piano string vibrates. The wooden sounding board increases the loudness and the sound quality.

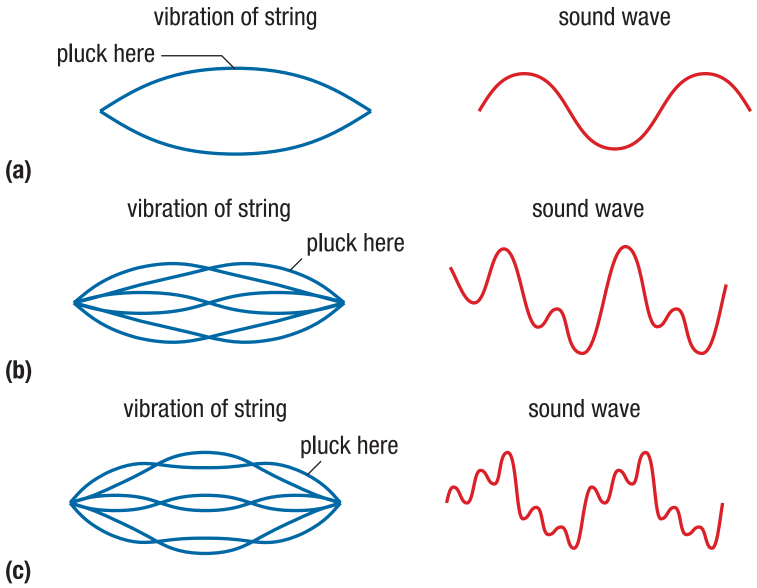


Figure 4 Changing the quality of sound produced by a vibrating string (a) First harmonic (b) Superposition of first and second harmonics (c) Superposition of first and third harmonics

Stringed instruments that are played using a bow usually belong to the violin family, which includes the viola, cello, violin, and string bass. The bow has long fibres on one side that are rubbed with rosin (a substance produced from tree resin) to increase the coefficient of friction. When stroked across a string, the bow causes the strings to vibrate. Each of the above instruments has four strings and two wooden sounding boards at the front and back of the case.

Some stringed instruments, such as the guitar, have frets that mark where the fingers of the non-strumming hand can be placed. When you press your finger against a string and then down onto a fret, you are effectively changing the length of the string by turning that point into a fixed end (node). This change in length changes the frequency at which the string will resonate, which changes the pitch. The members of the violin family do not have frets. This allows the frequency to be changed gradually rather than in steps.

FREQUENCY AND LENGTH OF THE STRING

Assume that a string fixed at both ends is plucked in the middle, producing an antinode at the fundamental frequency, similar to the example in Figure 4(a) on page 455. In this case, the length of the string represents half the wavelength and we can write $L = \lambda/2$, where L is the length of the string. Rearranging, we have $\lambda = 2L$. Now substitute this expression into the universal wave equation:

$$v = f\lambda$$
$$v = f(2L)$$
$$\frac{v}{2} = fL$$

If the tension is constant, then the speed of the wave is also constant, which implies that the quantity fL is also constant. We can write this new relationship as

$$\boxed{f_1L_1 = f_2L_2}$$

This equation implies that if you decrease the length of the string by pressing down on a fret, then the frequency of vibration must increase to keep the product of the frequency and length constant. You will see this equation applied in Tutorial 1.

Tutorial 1 Waves in Strings

The following Sample Problem will clarify the concepts of waves in strings when the length of the string is changed.

Sample Problem 1: A Wave in a Guitar String

A 0.650 m guitar string vibrates with a fundamental frequency of 120.2 Hz. The guitar player pushes the string down on the fret and changes the length of the string to 0.570 m.

(a) What is the new fundamental frequency of the string?

(b) Show that the speed of the wave in the string remained the same when the length was changed.

Solution

(a) **Given:** $L_1 = 0.650$ m; $f_1 = 120.2$ Hz; $L_2 = 0.570$ m

Required: f_2

Analysis: Use the relationship $f_1L_1 = f_2L_2$ to determine the new fundamental frequency.

Solution: $f_1L_1 = f_2L_2$

$$f_2 = \frac{f_1L_1}{L_2}$$
$$= \frac{(120.2\text{ Hz})(0.650\ \cancel{\text{m}})}{0.570\ \cancel{\text{m}}}$$
$$f_2 = 137\text{ Hz}$$

Statement: The new fundamental frequency is 137 Hz.

(b) Calculate the wavelengths in the string before and after the player pressed on the string, as well as the speed of the waves in each string. Then compare answers.

String before Pressing	**String after Pressing**
Given: $L_1 = 0.650$ m; $f_1 = 120.2$ Hz	**Given:** $L_2 = 0.570$ m; $f_2 = 137.1$ Hz
Required: v_1	**Required:** v_2
Analysis: $\lambda = 2L$ and $v = f\lambda$	**Analysis:** $\lambda = 2L$ and $v = f\lambda$
Solution: $\lambda_1 = 2L_1$	**Solution:** $\lambda_2 = 2L_2$
$\lambda_1 = 2 \times 0.650$ m	$\lambda_2 = 2 \times 0.570$ m
$\lambda_1 = 1.3$ m	$\lambda_2 = 1.14$ m
$v_1 = f_1\lambda_1$	$v_2 = f_2\lambda_2$
$= (120.2\text{ Hz})(1.3\text{ m})$	$= (137.1\text{ Hz})(1.14\text{ m})$
$= 156.3$ m/s	$= 156.3$ m/s
$v_1 = 156$ m/s	$v_2 = 156$ m/s

The speed of the waves in the longer string is 156 m/s. The speed of the waves in the shorter string is 156 m/s.

Statement: The speeds are equal. Therefore, changing the length of the string did not change the speed of the waves.

Practice

1. A guitar string is 63 cm long and has a fundamental frequency of 110 Hz. How long should the string be to produce a fundamental frequency of 150 Hz? T/I [ans: 46 cm]
2. A violin string is 22 cm long with a wave speed of 140 m/s. T/I
   (a) Calculate the fundamental frequency of the string. [ans: 320 Hz]
   (b) Calculate the fundamental frequency of the string if the length is decreased by 15 % by pressing the string on a fret. [ans: 370 Hz]

Wind Instruments

Wind instruments contain at least one resonant air column, and most are open air columns. The frequency with which the column resonates depends on the length of the air column and whether the ends are open or closed. Longer air columns produce lower-frequency sounds, and shorter air columns produce higher-frequency sounds. The long air column in a vuvuzela (vu-vu-SAY-la), popular with soccer fans (**Figure 6**), produces a loud, low-frequency sound.

The source of the sound in a wind instrument may come from air vibrating over an opening (flute), vibrating lips on a brass instrument (trumpet, trombone), or a vibrating reed—a thin strip of material (oboe, clarinet). In some wind instruments, such as the trombone, the length of the air column can be changed, which in turn changes the frequency of the sound produced (**Figure 7**). In other wind instruments, such as the pipe organ, the length of the air column is fixed. In a pipe organ, different air columns are used to produce different frequencies. In other cases, the length of the air column is fixed but the resonant frequency can be altered by opening or closing holes in the column (clarinet, recorder, and trumpet).

Figure 6 The vuvuzela is popular with soccer fans.

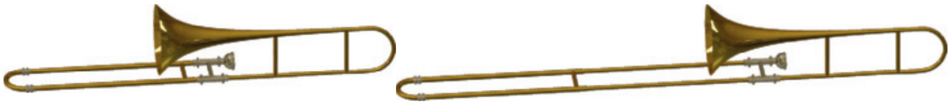


Figure 7 Changing the length of the air column changes the frequencies that resonate inside the column. The bends in the air column have no effect on resonance. They simply help make the instrument more compact.

CAREER LINK

There are many job opportunities for audio engineers; for example, recording musical artists, post-production for movies and television, and producing sound components for video games. To learn more about becoming an audio engineer,

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The quality of sound produced by a wind instrument depends on the skill of the musician, the quality of the instrument, and the resonant frequencies in the air column. Recall that a standing wave pattern is set up in an air column when resonance occurs. In wind instruments, not only is the fundamental frequency (first harmonic) present, but higher harmonics are also present simultaneously. Generally, the loudest frequency detected is due to the fundamental frequency, which is used to determine the note you hear. However, the combination of harmonics produces a more complex wave pattern, which increases the quality of the sound.

Consider an instrument that uses an open air column resonating with antinodes at both ends and one node in the middle (**Figure 8(a)**). In this case, the first harmonic (f_0) is produced and the wavelength is twice the length of the air column. The corresponding waveform as seen on an oscilloscope, for example, is shown beside the air column in Figure 8(a). Assume that the length of the air column is constant when a second standing wave is produced in the air column. To produce another standing wave, a higher frequency is required, which can be achieved by various means, such as blowing harder. For example, we can double the frequency ($2f_0$) and produce a wavelength half as long (**Figure 8(b)**). If the waveform for the first harmonic is combined with the waveform for the second harmonic, a higher-quality sound is produced (**Figure 8(c)**). If other harmonics are present in this open air column ($3f_0$, $4f_0$, . . .), they will further enhance the quality.

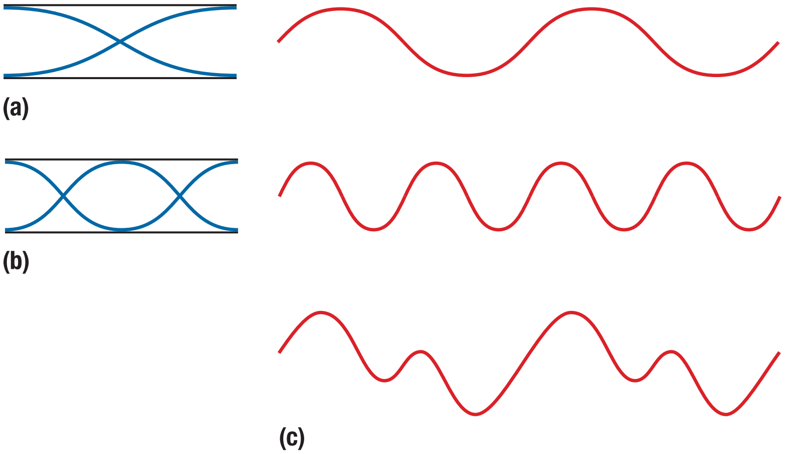

Figure 8 The quality of sound in a wind instrument depends in part on the harmonics present. (a) First harmonic (b) Second harmonic (c) Resulting waveform due to first and second harmonics

Recall from Chapter 9 that the higher harmonics for an open air column are always whole-number multiples of the fundamental frequency. Most wind instruments are open air columns. An air column that is closed at one end has higher harmonics that are odd-number multiples of the fundamental frequency (f_0, $3f_0$, $5f_0$, . . .). This will change the quality of sound produced because the resulting waveform will be caused by different frequencies. The clarinet is an example of a wind instrument that acts like a closed air column.

The resonant lengths of air columns are directly related to the wavelength of the sound inside the column. However, if the temperature changes, then the speed of sound changes, which in turn changes the wavelength of sound. Since the length of the air column determines the resonant frequencies, wind instruments should be tuned by adjusting the length of the air column to account for these changes in wavelength.

Figure 9 Several examples of percussion instruments

Percussion Instruments

To produce a sound with a percussion instrument, you strike one object against another. The instrument is usually struck by a firm object, such as a stick, a hammer, or a bar. Some examples of percussion instruments are shown in **Figure 9**. There are three categories of percussion instruments: single indefinite pitch, multiple definite pitch, and variable pitch.

Single indefinite pitch instruments produce more than one frequency at a time, and no one pitch can be heard above the others. Examples are the triangle, the bass drum, and castanets. Single indefinite pitch instruments are often used to keep the beat of the music. Multiple definite pitch instruments produce different resonant frequencies. They include tuning forks, orchestra bells, the marimba, the xylophone, the carillon, and bars or bells of different sizes. Variable-pitch instruments can rapidly change the pitch to a limited set of frequencies. An example is the kettledrum (or timpani), which has a foot pedal that can be used to change the pitch.

The head of the kettledrum is fabric stretched over a large copper (or fibreglass) bowl (**Figure 10(a)**). You cannot tune most drums; that is, you cannot adjust the frequency produced by most drums. Kettledrums, however, are always tuned to a specific pitch. To tune a kettledrum, you press on the foot pedal. When the pedal is pressed, it changes the tension in the head, which then changes the resonant frequencies of the head. When the head of the kettledrum is struck, the head vibrates up and down. The vibrations move into the large bowl and reflect off the inner surface. The reflected waves then pass out through the top of the drum and interfere with each other, giving the drum a rich, booming sound (**Figure 10(b)**).

Investigation **10.2.1**

Waveforms of Instruments (p. 476)
In this investigation, you will use what you have learned about instruments to compare their waveforms and try to identify the different harmonics.

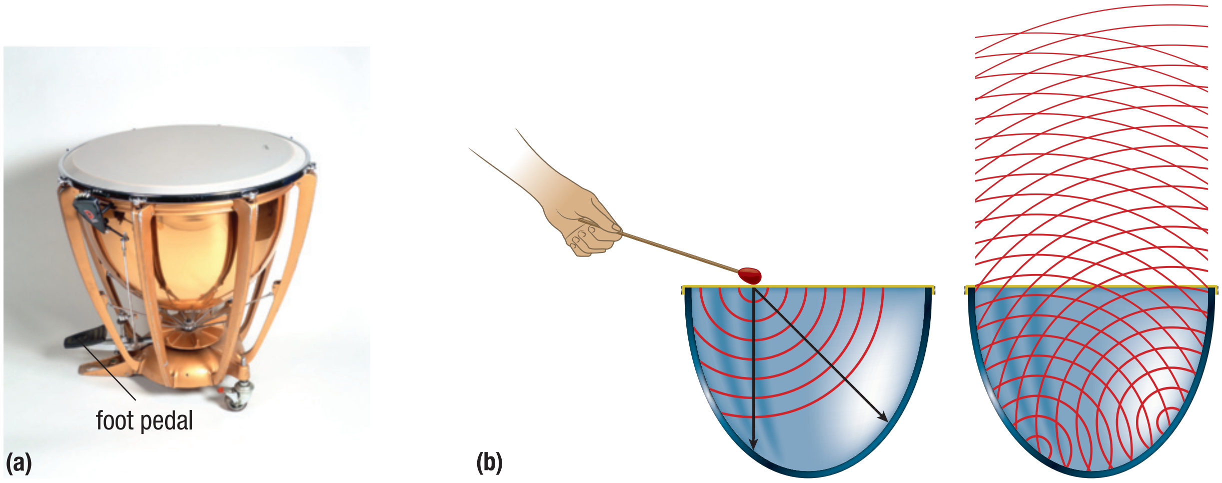

Figure 10 (a) A typical kettledrum, or timpani (b) Sound waves from the head of a kettledrum reflect off the inner surface of the bowl and interfere as they pass out through the top of the bowl. This diagram shows the reflection of the waves from only two points. The actual interference pattern is much more complicated.

10.2 Summary

- Music is a combination of musical notes (standing waves) produced from a source or sources with constant frequencies. Noise is sound produced from a source with constantly changing frequency and amplitude.
- Pitch, loudness, and quality are three subjective characteristics of sound because they depend on the perception of the listener. Pitch increases when frequency increases. Loudness increases when the amplitude of the sound wave increases.
- Musical quality depends on the number of harmonics.
- Musical instruments produce sound with a vibrating source. Most instruments are structured to enhance the sound using resonance.
- Stringed instruments consist of vibrating strings and a resonator, which resonates with the string. The resonator improves the loudness and quality of the sound produced.
- Wind instruments are composed of open or closed air columns. Vibrations are produced by vibrating lips or vibrating air over the opening or reeds.
- Percussion instruments produce sound by striking one object against another.

UNIT TASK **BOOKMARK**

As you carry out the Unit Task on page 486, apply what you have learned, about how each type of musical instrument produces sound, to your research or design project.

10.2 Questions

1. Each waveform in **Figure 11** represents a musical sound. Which one represents the highest (a) pitch? (b) loudness? (c) quality? K/U

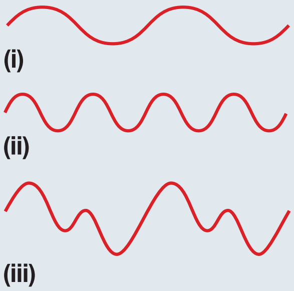

Figure 11

2. You place a string, fixed at both ends, under tension. When the string vibrates, it produces a sound that has no musical quality. Explain why. K/U
3. A sonometer (**Figure 12**) is a sounding board with at least one string whose length and tension can be varied. Why does a sonometer produce sound with higher quality than the string in Question 2? K/U

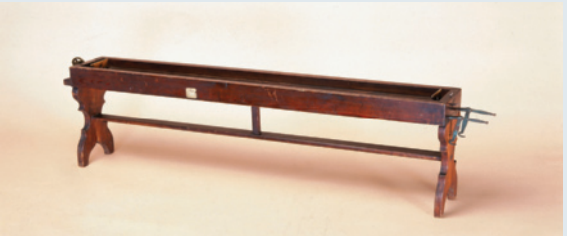

Figure 12

4. A guitar string with a length of 0.66 m vibrates with a fundamental frequency of 140 Hz. The player presses down on the string on top of a fret, decreasing the length by 11 cm. Calculate the new fundamental frequency. K/U
5. A 0.60 m string is stretched between two fixed points and vibrates with only one crest at a frequency of 120 Hz. K/U T/I
   (a) What is the wavelength in the string?
   (b) What are two other resonant frequencies for this string that could improve the quality of the sound?
   (c) What is another way to improve the quality of the sound?
6. If you twirl a long, flexible, corrugated plastic tube around your head in a circle, a musical note is produced. T/I
   (a) Why is a musical note produced?
   (b) What happens to the pitch of the musical note if the frequency of rotation is increased?
7. Use diagrams and the universal wave equation to show that an air column of fixed length will resonate with only
   (a) whole-number multiples of the fundamental frequency if the column is open at both ends
   (b) odd-number multiples of the fundamental frequency if the column is open at one end and closed at the other K/U T/I C
8. You tune a wind instrument inside when the temperature is 22.0 °C. You then bring the instrument outside where the temperature is 11.0 °C. Assume that the instrument acts like an open air column of length 0.800 m. K/U T/I
   (a) Predict how the fundamental frequency (first harmonic) will change when you go from inside to outside. Explain your answer.
   (b) Calculate the fundamental frequency for the instrument when it is
      (i) inside
      (ii) outside
9. You are constructing a wooden case box for a 420 Hz tuning fork to improve the loudness and quality of the sound. What is the minimum length of the box if the temperature is 24 °C and the box is
   (a) open at both ends?
   (b) open at one end and closed at the other? T/I
10. Organ pipes, which are open at one end, of lengths 23.0 cm, 30.0 cm, and 38.0 cm, resonate best at their fundamental frequency. If the speed of sound in air is 342 m/s, calculate
   (a) the wavelength of the sound produced by each pipe
   (b) the fundamental frequency produced by each pipe T/I

Acoustics

10.3

In ancient times, people would gather to watch plays and listen to music in theatres like the one in **Figure 1**. It was as important then as it is today for people to be able to hear clearly and for the music to be of high quality. Some people say their voice has a higher quality in the shower than anywhere else. Others notice that the sound quality of one theatre or large room is better than that of another. **Building acoustics** is the total effect of sound produced in an enclosed or restricted space.

building acoustics the total effect of sound produced in an enclosed or restricted space

Acoustics of a Room

When sound is produced in one part of a room, it spreads out toward the walls, where it can reflect or be absorbed. One of the main factors contributing to the acoustics of a room is the number and intensity of the reflections, or echoes. Without any echoes the music sounds flat, while too many echoes make the music sound muddy. When designing a room's acoustic qualities, the goal is to use echoes to improve the sound quality as much as possible and to ensure that everyone can hear clearly. The direct sound (sound that does not reflect from anything) should come from the stage to the audience. Several early reflections (reflections that take minimal time to reach the audience) should be directed at the audience, as shown in **Figure 2**. However, subsequent reflections should be minimized to improve sound quality.

Figure 1 The Roman theatre in the city of Amman in Jordan. The principles of acoustics have been applied to theatres since ancient times.

Reverberation Time

In some theatres, the music continues for a short time even after the musicians have stopped. This continuation of the music is due to echoes. **Reverberation time** is the time for the sound to drop by 60 dB from its maximum loudness or to drop to an inaudible level. In a well-designed concert hall the reverberation time is at most 1 s or 2 s. If reverberation times for a concert hall are too long, the sound quality is lessened. Reverberation time is the most important factor of sound quality in a concert hall.

You can change the reverberation time by changing the texture or materials in the wall, ceiling, and floor coverings and even changing the furniture. The presence or absence of an audience can also affect reverberation time. When designing a concert hall with reverberation time in mind, factors such as the length of the hall, the height of the ceiling, and the slope of the floor and ceiling must be considered. Materials such as brick and concrete reflect sound easily and increase the reverberation time due to subsequent echoes. Other materials found in acoustic tiles, the seats, and the audience will absorb more sound and reduce the reverberation time because subsequent reflections will be much quieter. Comparative absorption coefficients are given in **Table 1**. Substances with larger coefficients have greater sound-absorption qualities and, hence, shorter reverberation times. Notice from Table 1 that the absorption of sound by a material also depends on the frequency of the source.

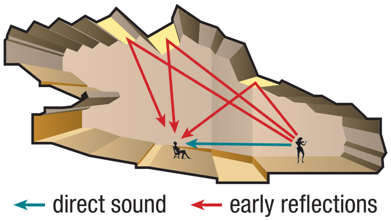

Figure 2 The design of this auditorium allows both direct sound and several early reflections to reach the audience.

reverberation time the time required for the loudness of the sound to drop by 60 dB or until the sound is inaudible

Table 1 Sound Absorption Coefficients for Various Materials*

Substance	Frequency (512 Hz)	Frequency (2048 Hz)
concrete	0.025	0.035
brick	0.03	0.049
wood (pine)	0.06	0.10
carpet	0.02	0.27
fibreglass	0.99	0.86
acoustic tile	0.97	0.68
theatre seats	1.6–3.0	—
seated audience	3.0–4.3	3.6–6.0

* To simplify the table, units have been omitted.

Investigation **10.3.1**

Investigating Acoustic Surfaces (p. 477)

In this investigation, you will use what you have learned about acoustics to design a soundproof box to reduce the amount of loudness of a sound source.

CAREER **LINK**

Acoustical engineers help design halls and theatres to improve the sound heard by the audience. To learn more about becoming an acoustical engineer,

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Problems may result when a room is designed to be used for many different purposes. The acoustics for a speech are not the same as the acoustics for a concert. Typically, rooms designed for speaking should have much shorter reverberation times than those designed for music. Choral music (large groups of people singing together) requires reverberation times from 2 s to 5 s. In addition, large rooms require longer reverberation times than smaller rooms. Acoustical engineers have a challenging task when designing a large room to be used for many purposes.

Designing Spaces for Acoustics

When designing a room with acoustics in mind, designers try to avoid curved surfaces. When sound reflects off curved surfaces, it becomes either more concentrated or more dispersed (spread out). From a concave surface the reflected sound becomes concentrated at a single focal point, making the sound uncomfortably loud, while people nearby hear little or no sound (**Figure 3(a)**). If the surface is convex, the sound intensity drops off more quickly than usual, making it much more difficult to hear clearly (**Figure 3(b)**). Most surfaces should be flat to avoid these issues (**Figure 3(c)**).

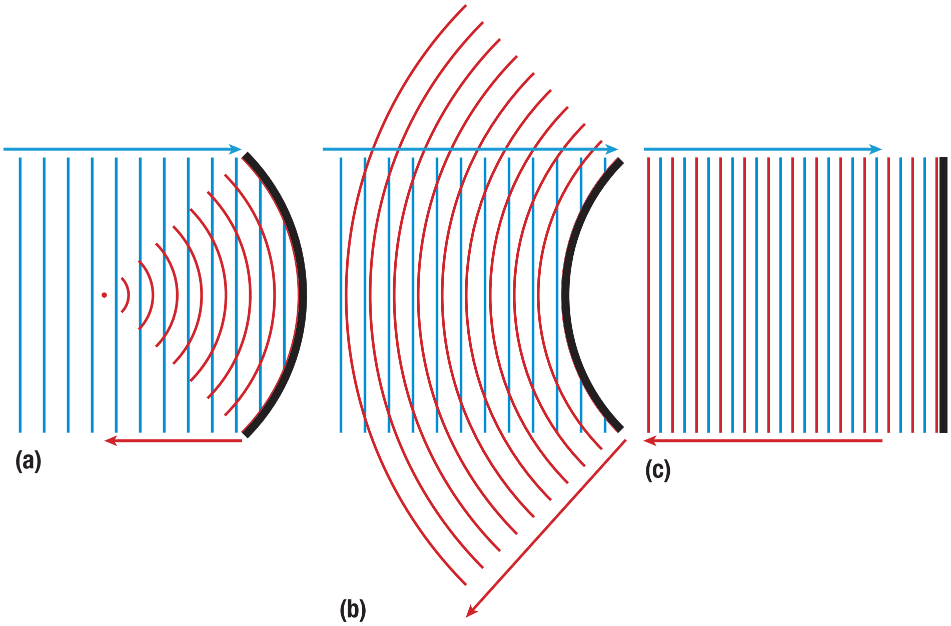


Figure 3 (a) A concave wall reflects sound to a single focal point. (b) A convex surface reflects sound so that the sound waves are dispersed. (c) Flat surfaces reflect sound evenly.

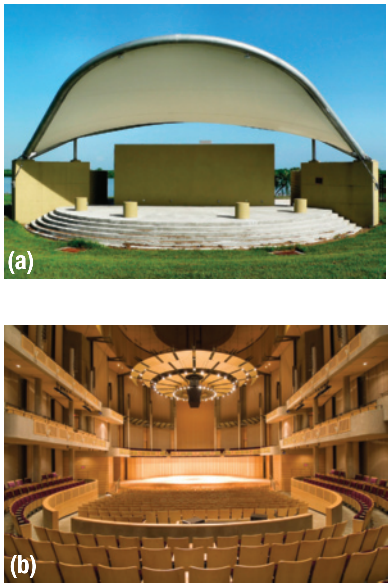


Figure 4 (a) The parabolic shape of an outdoor band shell works well outdoors. (b) The Chan Centre for the Performing Arts in Vancouver, British Columbia, uses many different acoustical principles to produce an intimate musical experience.

However, curved surfaces are used in the design of outdoor band shells, which are often in the shape of a parabola with the performers at the focal point (**Figure 4(a)**). In this design, a person speaking with a normal voice on stage can be heard by everyone in the outdoor theatre. Using curved surfaces indoors is not a good design. The curved surfaces would focus the reflected sound waves back toward focal points in the audience.

Another problem that can arise from a poor design is acoustical shadow. An acoustical shadow occurs when compressions and rarefactions combine in an area of the seating to produce destructive interference. The resulting reduction in loudness can make it difficult for an audience member to hear the performance.

Many present-day theatres, such as the one shown in **Figure 4(b)**, have numerous design features that produce acoustical effects unique to the building. There are many different terms to describe the acoustical properties of these rooms. For example, an intimate room is one where the first early reflection reaches the audience less than 20 ms after the direct sound. A live room is one with a longer reverberation time. In some rooms, much of the sound energy is absorbed and only a portion is reflected. In other rooms, more of the sound energy is reflected. A full room means the reflected sound intensity is very close to the direct sound intensity.

Devices such as speakers, microphones, and telephones must sometimes be tested in an environment that has a reverberation time as close to zero as possible. These anechoic (ann-e-KO-ick) rooms are designed by carefully choosing the materials in the room to make it acoustically dead. The term "anechoic" means without echo. As the name implies, the materials absorb most of the sound energy and reflect as little as possible.

10.3 Summary

- The properties of sound influence the design of structures.
- Building acoustics is the total effect of sound produced in an enclosed or restricted space.
- Reverberation time is the time for the sound to drop by 60 dB from its maximum intensity or to drop to an inaudible level.
- The materials, textures, shape, and size of a room are some of the factors that affect a room's acoustics.

UNIT TASK **BOOKMARK**

As you carry out the Unit Task on page 486, apply what you have learned about how acoustics can influence the design of your researched structure or your device.

10.3 Questions

1. A concert has a loudness of 82 dB. What will the sound level drop to after the reverberation time? T/I
2. The graph in **Figure 5** is used to determine the reverberation time for a theatre. T/I

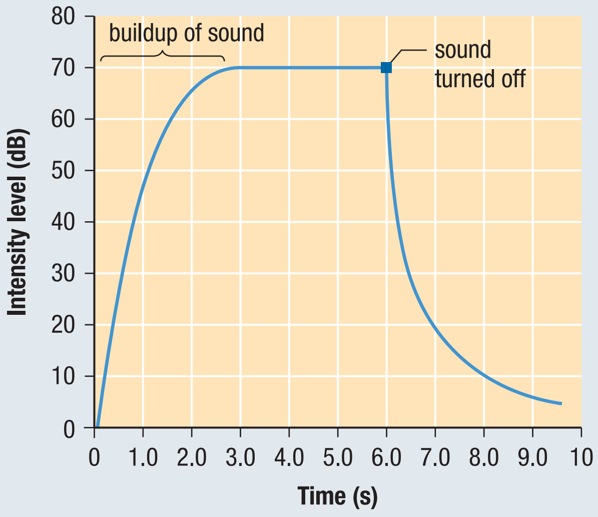


Figure 5

   (a) What is the reverberation time for the theatre?
   (b) What could be done to decrease the reverberation time?
   (c) What could be done to increase the reverberation time?
3. Auditorium A has wooden-backed seats, and auditorium B has cloth-covered, padded theatre seats. How will the acoustical properties of the two theatres compare when they are (a) empty and (b) full? Explain your reasoning. K/U C
4. When a theatre is adjusted to accommodate choral music instead of a speaker, the theatre staff often remove large curtains from the wall and adjust the ceiling features. Explain why they make these adjustments. K/U
5. Why is it preferable to have short reverberation times for auditoriums where speeches are performed and longer reverberation times for auditoriums where music is performed? K/U
6. What features need to be incorporated into the acoustic design of an outdoor concert venue in order for it to provide optimal sound quality for the audience but limited noise in the surrounding area? K/U
7. In a large room with one wall covered by windows, a speaker's words seem to lack clarity. Will closing the curtains help? Explain your answer. K/U T/I
8. Examine an enclosed space like a stage or an auditorium in your school or community for acoustical design features. Find out the primary purpose of the room (lectures, music, and so on), and then list some of the acoustical design features in the room. A
9. Why are few if any acoustical design features required in an average classroom in your school? A

10.4 Structural Safety

On July 1, 1940, the Tacoma Narrows Bridge, in Tacoma, Washington, was completed. On November 7, 1940, the main span of the bridge collapsed during winds of 64 km/h (**Figure 1**). The bridge was built to withstand winds of far greater speed. How could such a large structure, over 12 m wide and almost 1 km long, fall so easily? In this section, you will learn how the physics of waves can improve the safety of structures such as bridges and buildings.

WEB **LINK**

To see a video of the Tacoma Narrows Bridge during the high winds in 1940,

GO TO NELSON SCIENCE

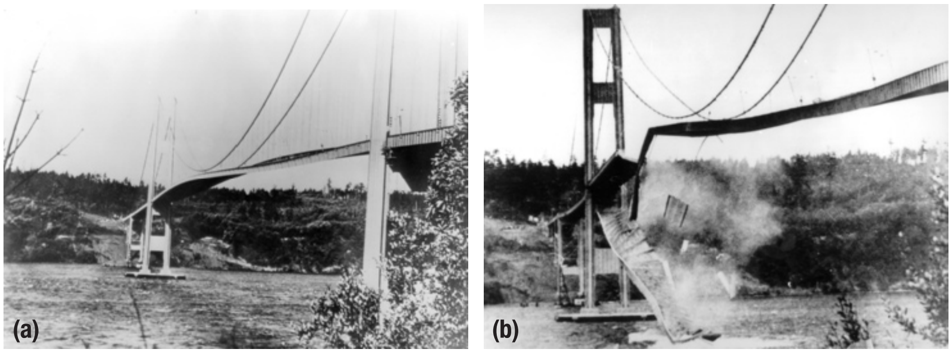


Figure 1 Physicists believe that waves had a lot to do with the collapse of the Tacoma Narrows Bridge in 1940. (a) The centre span of the Tacoma Narrows Bridge began vibrating because of the wind. (b) Eventually, built-up energy in the vibrations caused extremely large amplitudes, and the bridge collapsed under the strain.

Mechanisms Causing Vibrations

mechanical resonance the transfer of energy from one object to another, causing large-amplitude vibrations when the second object has the same resonant frequency as the first

In Section 9.4 you were introduced to resonance. **Mechanical resonance** occurs when there is a transfer of energy from one object to another with the same natural or resonant frequency. The child–swing system is an example of mechanical resonance, because there is physical contact between the periodic force applied (the source of the vibrations) and the vibrating object.

Consider the series of pendulums suspended from a taut string in **Figure 2**. When pendulum A is set to vibrate, pendulum E will also start to vibrate. As E gains amplitude, A loses amplitude. Eventually, E will develop large amplitudes and A will hardly move at all. During this time, the other pendulums will move slightly but never develop large amplitudes. The energy from A is transferred through the string to the other pendulums. However, only pendulum E, with the same natural frequency, begins to vibrate in resonance. This is called **sympathetic vibration**, and it occurs when one object vibrates in resonance with another of the same resonant frequency.

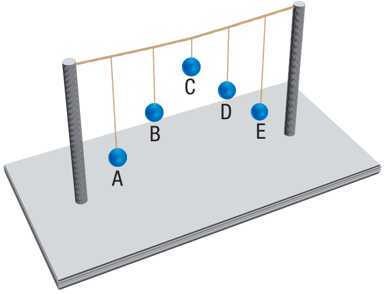


Figure 2 A series of pendulums can demonstrate sympathetic vibrations.

Another mechanism that can cause objects in air to vibrate with large amplitudes is **aeroelastic flutter**. This happens when more energy is added to the vibrations than can be lost to the natural damping of the structure. It occurs when the wind exerts a force on a structure due to the aerodynamics of the structure. The elasticity of the structure allows it to vibrate.

There is significant disagreement among scientists on the primary cause of the collapse of the Tacoma Narrows Bridge. Physicists believe that mechanical resonance was the primary cause, but engineers believe that aeroelastic flutter was the primary cause. A generally accepted cause is that the wind transferred more energy to the bridge during each vibration than it could lose during the same vibration. This caused torsional vibrations: one side of the bridge moved up when the other moved down, with the centre of the bridge remaining at rest. Eventually, enough energy built up to cause extremely large amplitudes of vibration, and the bridge collapsed under the strain. Engineers now ensure that new structures can withstand wind speeds higher than the wind speeds possible in the area of the structure.

sympathetic vibration the response to a vibration with the same resonant frequency

aeroelastic flutter the response when the energy added to a structure vibrating in air exceeds the energy lost due to damping, causing large vibrations

Vibrations in Buildings

Large vibrations in buildings can be caused by earthquakes. For most areas, however, they are caused by wind. Tall buildings constructed before World War II were built with concrete, which resists compressions well but is not very flexible. If a concrete skyscraper starts to sway, the concrete can crack and the building can fall. To prevent this, engineers strengthened the buildings with massive, thick walls. In addition, the engineers added steel bars, which can bend slightly, to the rigid concrete to improve flexibility. A good example of this type of construction is the Empire State Building in New York City (**Figure 3**). However, this method is very expensive, and as skyscrapers were made taller, engineers had to find new technologies to construct them.

After World War II, skyscrapers were built with a series of huge metal pillars (girders) that act as the frame for the building. The actual walls (called curtain walls) on the outside of the building are glass and act as weatherproofing rather than structural support. However, as more tall buildings go up in a small area, wind is forced into a relatively narrow street, causing an increase in wind speed. This occurs because the same amount of air must pass through a smaller space. Engineers must take this increase in wind speed into account when designing new buildings. They must also consider people walking at street level.

Wind can cause some skyscrapers to sway up to 1 m at the top floor. Earthquakes can cause vibrations with even greater amplitudes. To help decrease the amplitude of these vibrations due to resonance or aeroelastic flutter, some buildings have a mass damper, usually consisting of a pendulum made out of concrete or steel. These dampers develop sympathetic vibrations, which take energy from the building when it vibrates, thus decreasing its amplitude. The dampers are designed to take the energy before it can return to the building. Sky lobbies (horizontal areas), which break up the design of a structure at different altitudes, also help by decreasing the surface area of the tower at higher elevations (**Figure 4**). This reduces the forces caused by winds.

Figure 3 The Empire State Building in New York City was built using massive concrete walls to reduce vibrations.

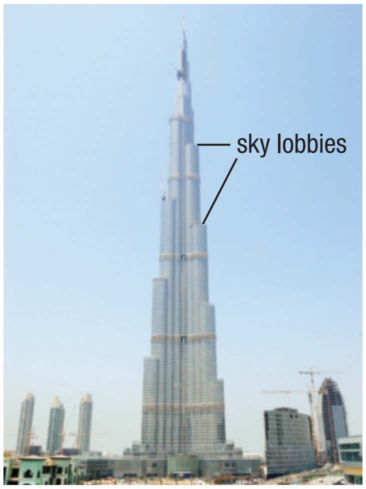


Figure 4 At 828 m, the Burj Khalifa, in Dubai, is the tallest structure ever built. Notice the sky lobbies in this structure.

10.4 Summary

- Mechanical waves can damage structures.
- Mechanical resonance occurs when a periodic force acts on an object at the natural or resonant frequency of the object. Mechanical resonance must be considered when designing structures and buildings.
- Aeroelastic flutter occurs when an object is vibrating in air and the input energy is greater than the energy lost due to damping.

10.4 Questions

1. Explain how you could apply the principles of mechanical resonance to a car when it is stuck in the snow. T/I A
2. When walking across a footbridge, some people notice that it moves up and down. One person suggests that they all march across the bridge together stomping their feet at the same time. Explain why this is a dangerous idea. T/I
3. If pendulum A in Figure 2 on page 464 starts swinging back and forth, then pendulum E will develop sympathetic vibrations. K/U T/I C
   (a) Explain why this happens.
   (b) What do you think will happen if pendulum E has a large amplitude swing?
   (c) As pendulum E gains amplitude, pendulum A loses amplitude. Explain why.
   (d) Describe how to use a beaker filled with water to make pendulum E into a mass damper similar to those found in some skyscrapers. Explain how it works.
4. Give two reasons why large concrete walls are no longer used when constructing skyscrapers. K/U
5. In a Venn diagram, compare and contrast mechanical resonance and aeroelastic flutter. K/U C
6. In your own words, describe why the Tacoma Narrows Bridge collapsed when the wind speed was only 64 km/h. K/U C
7. Research building safety. Find a technology not mentioned in this text that is used to reduce vibrations in buildings during windy conditions or during an earthquake. Determine the effectiveness of the technology. Write a short assessment of your findings. T/I C

GO TO NELSON SCIENCE

10.5 Seismic Waves

tsunami an enormous sea wave or a series of enormous sea waves caused by an earthquake or other disturbance

seismic waves waves of energy that travel through Earth

On December 26, 2004, in one of the worst natural disasters in recorded history, a deadly tsunami (su-NAH-me) devastated several countries, including Indonesia, Sri Lanka, India, and Thailand, killing over 230 000 people (**Figure 1**). A **tsunami** is an enormous sea wave or a series of enormous sea waves caused by an earthquake or other disturbance. The waves generated in the 2004 tsunami were as high as 30 m. In this section, you will study the physics of earthquakes and seismic waves, as well as how seismic waves can be used in geophysical exploration. **Seismic waves** are waves that carry energy through Earth.

Figure 1 The 2004 tsunami as it hit the coast of Thailand

Earthquakes

Earth's crust (surface) is made up of several large tectonic plates that fit together like a spherical puzzle. These tectonic plates are slowly moving, and they can move apart, push together, or slide against each other along regions called fault lines (**Figure 2**). However, these plates have jagged edges that can catch on each other as they press together along fault lines, building up tremendous pressure. The pressure builds up to the point where the plates slip along the fault lines, causing an earthquake.

Once two plates slip faster than usual along a fault line, seismic waves are created that can travel either along Earth's surface (surface waves) or into Earth itself (body waves). Whenever waves pass through Earth's surface or reach the surface, they shake the ground, causing an earthquake. The speed of these waves increases with depth but also depends on the materials present.

There are two types of body waves—primary waves (P-waves) and secondary waves (S-waves). These waves follow curved paths through Earth because they refract (bend) due to variations in density and stiffness. This is similar to the way light refracts when it passes through transparent media. P-waves are longitudinal waves and move almost twice as fast as S-waves. S-waves are transverse waves that arrive after the P-waves because of the S-waves' slower speed.

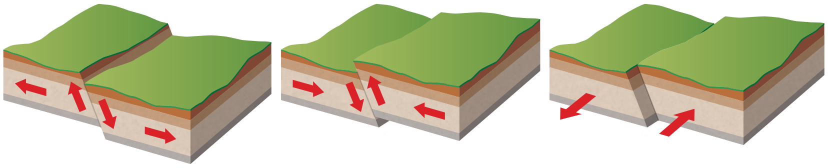


Figure 2 The relative motions of tectonic plates along fault lines

Surface waves are similar to water waves, and they move more slowly than body waves. They are more destructive than body waves because they tend to last longer, have a lower frequency, and have a larger amplitude.

As P-waves and S-waves move through Earth, they refract and curve back toward the surface. In addition, P-waves can move through both solid and liquid material, but S-waves can only travel through solid material. Using this information, scientists have determined much about Earth's interior. For example, scientists now believe Earth has a liquid outer core because S-waves cannot reach regions around the globe that P-waves can (**Figure 3**).

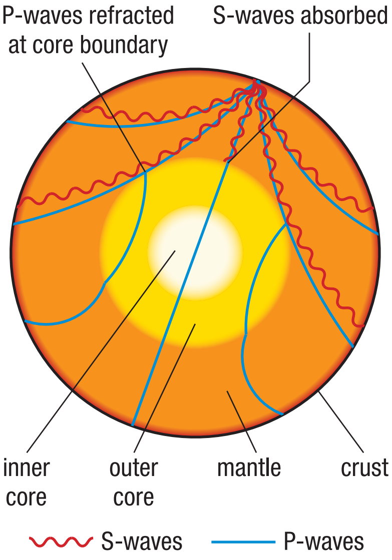
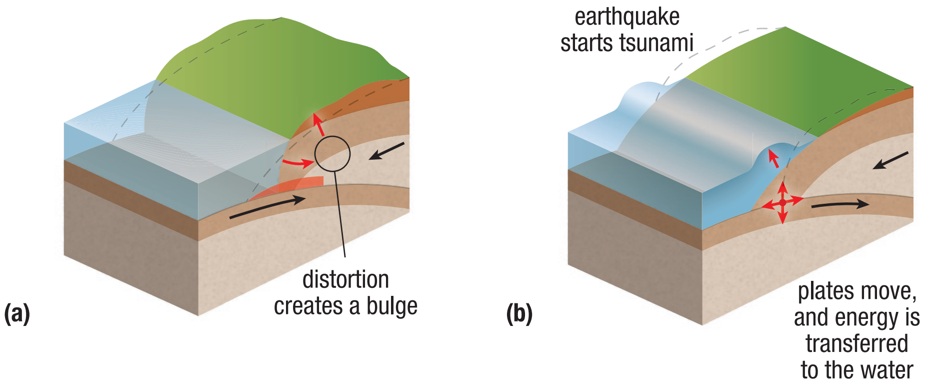


Figure 3 Body waves provide information about Earth's interior.

Seismic Waves and Tsunamis

When underwater tectonic plates shift suddenly and produce an earthquake underwater, a tsunami can be generated. As one plate slides over the other, it bulges. This bulging stores a tremendous amount of energy. When the plates start to move during an earthquake, the energy stored in the plates is transferred to the water. The energy in the water is transferred because a large volume of Earth is displaced, which causes a large volume of water to be displaced, creating conditions for the generation of a tsunami (**Figure 4**). Tsunamis gain amplitude as they approach shore.



(a)
distortion creates a bulge
(b)
earthquake starts tsunami
plates move, and energy is transferred to the water

Figure 4 (a) Pressure builds up between two tectonic plates. (b) The energy is released, creating a tsunami.

Research This

Tsunami-Warning Systems

Skills: Researching, Analyzing, Evaluating, Communicating, Defending a Decision

SKILLS HANDBOOK A5

Many coastal areas have tsunami-warning systems in place that help warn coastal residents about possible tsunamis. Such systems give residents time to move inland before the tsunami hits the coast. Nothing can warn residents of a sudden tsunami that occurs very close to shore, however.

1. Research tsunamis and tsunami-warning systems using Internet and/or print resources.

A. What impact can tsunamis have on coastal regions? K/U

B. Tsunami-warning systems are based on what fact? T/I

C. How effective are such systems in reducing death tolls and property destruction? T/I

D. Should all coastal regions have some sort of tsunami-warning system? Explain. C A

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Seismic Geophysical Exploration

Most minerals and fuels are deep underground—1000 m down or deeper. Drilling is time-consuming and expensive, so companies will not drill until they are reasonably sure something of value is beneath the ground. Different methods can be used to determine the nature of the materials underground without digging. Measuring changes in gravity and magnetic fields are two examples. We will focus on methods that use seismic waves to study Earth's interior. Enormous insight has been gained through seismic exploration in understanding Earth's internal structure.

When waves travel from one medium into another, the wave splits into two (Section 9.2). One part of the wave is reflected and the other part is transmitted. The same thing happens when a wave is produced underground. When a large vibration is produced in the ground from a small explosion or even just a heavy object striking the ground, sound waves move away from the source of vibration in all directions through the ground. These waves then pass through soil and rock and partially reflect and partially refract whenever they pass into a new layer. Information can be collected at the surface by recording channels that have different groups of extremely sensitive geophones (microphones that detect seismic waves) placed along the channel at regular intervals (**Figure 5**). This information is used to examine Earth's interior by tracing the rays backwards from the many sources to determine the location of the

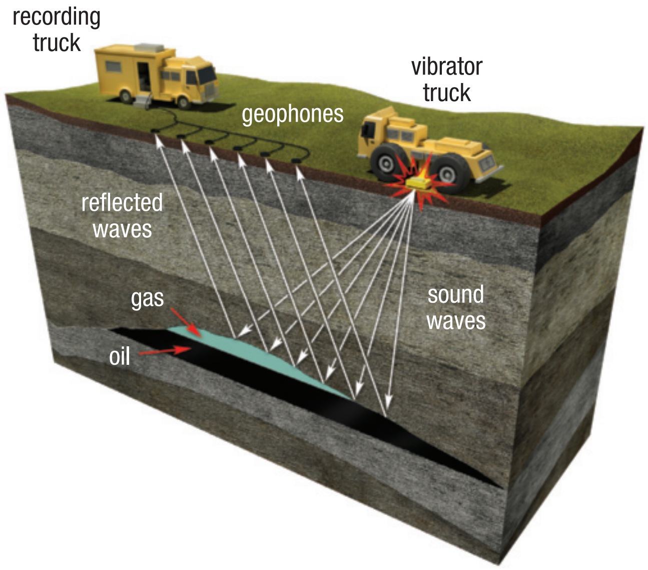

Figure 5 Sound waves produced by a vibrator truck travel through Earth and reflect off the various layers. The reflections eventually reach the surface, where they are recorded by geophones. Typically, the waves partially reflect off each layer beneath the surface. The process has been simplified in this diagram.

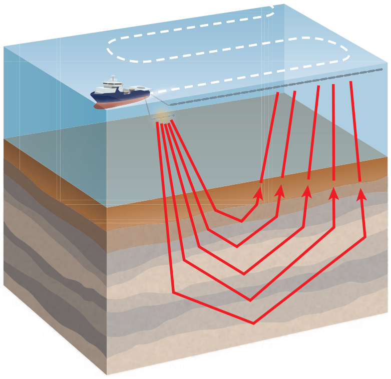

Figure 6 A ship using waves to search for oil beneath the ocean floor

layer that caused the reflection. Because of its complexity, the process is completely computerized.

Researchers then use the reflected seismic waves and computers to produce a detailed image of the underground layers. They examine the image to see how the waves reflected and how long the reflections took. From this examination, researchers determine the probable composition of the underground layers.

Using this information, researchers identify the depth of any valuable deposits, the size of the deposits, and where drilling should take place. This reduces the amount of drilling required, saving time and money. A similar method is used to find oil underneath the ocean floor using a ship moving in a zigzag pattern across the ocean surface (**Figure 6**).

A similar method has been used to explore the Moon. During the Apollo missions, sensitive seismic equipment was left on the Moon to collect seismic data about its interior. Other Apollo missions intentionally smashed booster rockets into the Moon's surface to cause vibrations, which were used to analyze the interior of the Moon.

UNIT TASK **BOOKMARK**

As you carry out the Unit Task on page 486, apply what you have learned about how seismic waves can influence the design of your researched structure.

10.5 Summary

- Earthquakes cause different types of waves that move through Earth and across the surface. Underwater earthquakes can cause tsunamis, which can damage coastal land and properties, as well as cause loss of life.
- Seismic waves can have a negative impact on society, but technologies can help reduce this impact.
- Seismic geophysical exploration can be used to form computerized images of layers of rock, liquids, and mineral deposits underground and under the ocean floor. These images can be used to determine depth, composition, and size of deposits and where to drill. This method of exploration saves both time and money.
- Similar seismic techniques involving waves have been used to study Earth's interior. Enormous insight has been gained through this method in understanding Earth's interior structure.

10.5 Questions

1. Explain the difference between (a) a surface wave and a body wave, and (b) a P-wave and an S-wave. K/U
2. Describe how P-waves and S-waves are useful in determining the nature of Earth's interior. K/U C
3. Scientists can detect both P-waves and S-waves and then use them to determine the location of the epicentre (the point of origin on the surface of the earthquake). Describe a procedure that could be used to determine the location of the epicentre if you know the speed of each wave. Assume that the waves have been detected at several different positions close to the epicentre. T/I
4. List three reasons why geophysical exploration is an important part of obtaining natural resources, such as oil and natural gas. K/U
5. Sound waves are used to map different layers of Earth. K/U
   (a) Describe the technology used to form a computerized image of the layers of rock and mineral deposits underground.
   (b) How are sound waves used to gather information to form these images?
6. **Figure 7** represents several layers of rock beneath Earth's surface. Copy the diagram into your notebook. A vibration is created at the surface at the point shown. Use your diagram to show how waves from the source could be reflected off the various layers of rock. K/U C

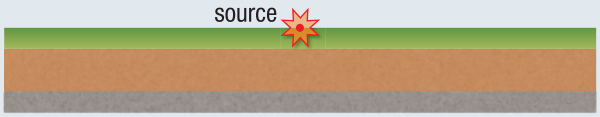

Figure 7

7. Research helioseismology. T/I
   (a) Explain what helioseismology means.
   (b) Explain how the Sun "rings like a bell."
   (c) Explain why we cannot hear the Sun's vibrations.

GO TO NELSON SCIENCE

Vibrations in Aircraft

10.6

Aircraft are used all over the world for many purposes, such as transportation of cargo, personal and business travel, and national security. Many of us take aircraft safety for granted. The safety record of commercial aircraft is outstanding because aircraft designers and engineers have put a tremendous amount of effort into their design.

Aircraft undergo many types of vibrations. Usually, passengers only notice minor vibrations, such as noise and flexing of the wings, which are normal and perfectly safe (**Figure 1**). There can be more serious, abnormal vibrations in aircraft, however, and aircraft designers and engineers constantly study these vibrations to make aircraft safer. In this section, you will learn about how vibrations can start in aircraft and what is done to minimize them.

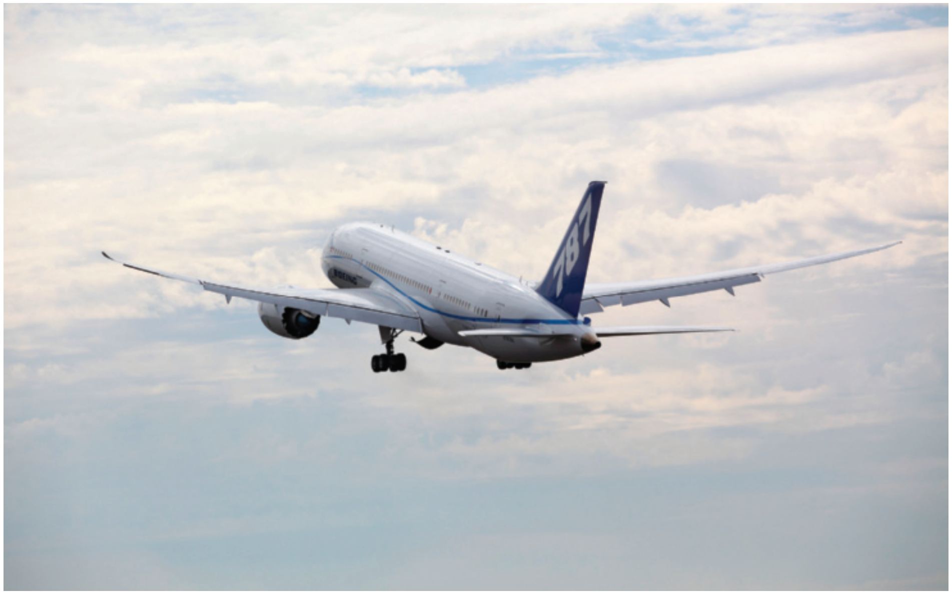

Figure 1 The wings of commercial airliners are designed and constructed to be flexible. Most wave motion that the wings experience is accounted for in the design.

Causes of Vibrations

Vibrations in modern aircraft have several causes, most of which are not unusual or dangerous. For example, vibrations happen during extension and retraction of landing gear, deployment of aerodynamic brakes (**Figure 2**), and takeoff and landing. The operation of the engines also produces constant vibrations. All these vibrations are expected and have been minimized by appropriate design features.

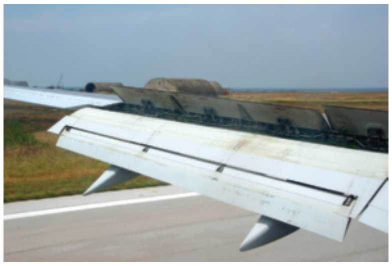

Figure 2 Aerodynamic brakes cause normal vibrations in aircraft.

Other normal vibrations experienced by an aircraft come from the mass distribution and the structural stiffness of the aircraft. Usually, very low-amplitude vibrations result when typical forces act on the aircraft due to airflow over the surfaces. Most passengers hear these vibrations as background noise. The vibrations get much larger in turbulent (rough) air, and passengers can actually feel them. Sometimes, when the engines are operating at certain levels, increased vibration may occur due to resonance. This is normal and often sounds loud only because the waves are transferred through the frame of the aircraft to the ears of the passengers. Even the operation of mechanical components such as pumps can cause some vibration in aircraft.

The flight crew quickly becomes familiar with normal aircraft vibrations. They detect these vibrations by sight, sound, and feel. As an added precaution, aircraft engineers put sensors in the engines in case abnormal vibrations start that are not detected by the crew. Each aircraft has different characteristics and slightly different but normal vibrations, but an experienced crew gets used to them.

Abnormal vibrations can be quickly recognized because they often occur suddenly and are accompanied by an unfamiliar noise. They can be steady or random, can have an obvious source, or can be difficult to pinpoint. Causes include malfunctions in mechanical equipment, an engine rotor imbalance, irregular airflow over an external part of the aircraft that is damaged or not closed properly, excessive wear, and free play (parts that can vibrate with little force acting on them).

Types of Vibrations

Buffet is a type of random vibration that is usually caused by an interruption of airflow. Buffet is often felt when the aerodynamic brakes (Figure 2, page 469) are used or when the aircraft flies through turbulence. In addition, a certain amount of noise is to be expected due to the operation of the engines. Aircraft noise is a vibration caused by the rapid back-and-forth movement of one part of the aircraft.

The most dangerous type of vibration in aircraft is aeroelastic flutter (or simply flutter). Recall aeroelastic flutter from the discussion of the Tacoma Narrows Bridge in Section 10.4. When the energy added to the vibration by the airflow around the wings of an aircraft is greater than the energy lost as a result of damping, the result is a rapid vibration, or fluttering, of the wings. If the wing flutter lasts long enough and has a large enough amplitude, it can cause the aircraft to fail.

WEB **LINK**

To see a video of flutter in the tail wing of an aircraft,

GO TO NELSON SCIENCE

Testing for Flutter

Flutter is very rare in modern aircraft, but it must be produced when testing new aircraft. One type of flutter test is called a pulse test. In a pulse test, the pilot controls the aircraft such that the airflow is suddenly and drastically disturbed around the wings. Engineers then monitor the wing flutter from the ground and study how the vibration decreases over time. If the aircraft does not pass the pulse test, then the engineers modify the design of the wing. If the aircraft passes the pulse test, then the engineers proceed to a sweep test.

In a sweep test, the engineers produce large computer-generated vibrations in the wing (**Figure 3(a)**). The computer controls the frequencies of the vibrations produced in the wings, and a wide range of frequencies is used, one at a time. To pass the sweep test, the flutter induced in the wing should dampen quickly; that is, within a few seconds after the computer-generated vibrations stop (**Figure 3(b)**). If an aircraft fails the sweep test, the engineers modify the design of the wing. Modifications include finding new ways to dampen the vibrations and making the wing more rigid. The wings cannot be made too rigid, however. If too rigid, they will eventually develop small fractures that can cause them to fail.

CAREER **LINK**

Many industries, including the aerospace industry, test vibrations to ensure product safety. To learn more about careers in the aerospace industry,

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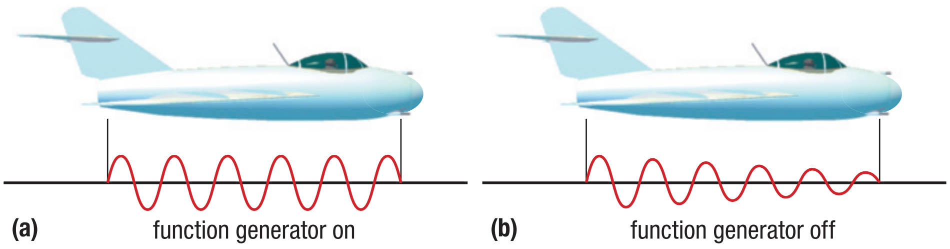


Figure 3 (a) When flutter is induced by a computer (function generator), the wing vibrates with large amplitudes. (b) When the function generator is turned off, a properly designed wing will vibrate with progressively decreasing amplitude.

New aircraft are designed so that flutter cannot occur at any normal flight speed or even when predictable malfunctions occur. In fact, the engineers design the aircraft to be flutter resistant under speeds and conditions far beyond the expected performance of the aircraft. If the aircraft flies at an abnormal speed, say, far beyond the design limits, or if a serious unpredictable event occurs, then flutter can occur on rare occasions.

Flutter can be distinguished from buffet because the flutter vibrations can occur in smooth air and seem to originate from the aircraft rather than from irregular airflow.

It is up to the flight crew to judge when and how they should respond to an abnormal vibration. The crew usually responds by levelling out the aircraft and decreasing the speed. If the problem persists or gets worse, the flight crew may decide to attempt an emergency landing at the nearest airport. This option is only used under the most extreme circumstances, when passenger safety is an issue.

Pogo in Rockets

Rockets can develop longitudinal vibrations during launch. During launch, the propellant pipes can experience low-frequency disturbances, which can periodically change the propellant flow rate. Since the propellant flow rate is changing periodically, it can affect the thrust of the rocket, which periodically increases and decreases several times in a second. Normally, the mass of the rocket is so large that the variations in thrust cause very little change in acceleration, so this effect goes unnoticed. However, if the frequency of the thrust vibrations matches the natural or resonant frequency of the rocket, then resonance can take place. In this case, the rocket will feel like it is surging back and forth like a pogo stick. Engineers eliminate the pogo effect by changing the length of the propellant pipes, which changes the frequency of the thrust vibrations. They also add dampers to the propellant pipes, which eliminate the pipe vibrations to help ensure that the flow rate is constant.

10.6 Summary

- Properties of mechanical waves influence the design of structures.
- Aircraft experience various vibrations. Most vibrations are normal and pose no threat to the operation of the aircraft.
- Aeroelastic flutter is the most dangerous type of abnormal vibration in aircraft, but modern aircraft rarely experience flutter.

10.6 Questions

1. Describe three normal types of vibrations in aircraft. Include one example for each. K/U C
2. Why is it so important that the flight crew of an aircraft monitor and respond to abnormal vibrations quickly on aircraft when similar vibrations in a car might be ignored? K/U
3. In a graphic organizer, compare aeroelastic flutter in a bridge and in an aircraft in terms of how flutter is caused and the effect on the object. K/U C
4. Explain why the flight crew of an aircraft is better at identifying abnormal vibrations than any passenger on the aircraft. K/U
5. List three ways that pilots and engineers can prevent or stop aeroelastic flutter once it has started. K/U
6. Describe the pogo effect in rockets by answering the following questions: K/U C
   (a) What causes the pogo effect?
   (b) Why is it called the pogo effect?
   (c) What can be done to prevent the pogo effect in rockets?
   (d) Describe one way you could demonstrate the pogo effect to your peers.
7. **Figure 4** is a diagram of a jet engine. Examine the figure, and explain why a jet engine might cause more serious vibrations if it becomes unbalanced. T/I A

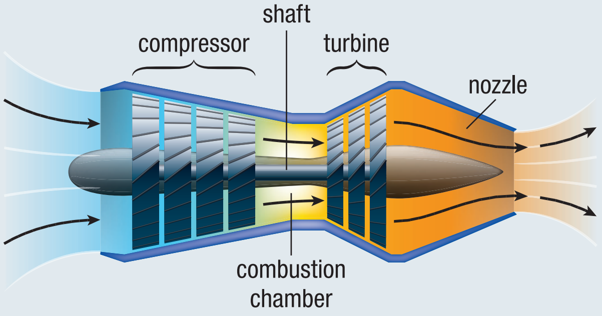


Figure 4

8. Research jet engines on the Internet or using print resources. How do the noise levels produced by different types of jet engines compare with each other? Organize your findings in a web page or format of your choice. T/I C

GO TO NELSON SCIENCE

10.7 Nature and Sound Waves

Bats can hardly see, yet they catch flying insects at night (**Figure 1**). Dolphins can catch fast-moving fish in murky waters, where visibility is extremely low. Elephants can find each other over distances of several kilometres, yet their eyesight is relatively poor. Household cats cannot see very well up close, yet they easily catch small houseflies that fly right in front of them. How do these animals perform these seemingly impossible tasks? The answer is that they use sound waves. In this section, you will learn some of the ways sound waves are used in nature.

Figure 1 Bats can hardly see, yet they catch insects at night in mid-flight.

Echolocation

Dolphins, sperm whales, and orca whales produce sound and detect the echoes to locate prey, navigate through the water, and communicate with others of their species in dark, murky waters. This process is called **echolocation**, which means using echoes, or reflected sound, to locate an object. These animals use a variety of frequencies (40 kHz to 130 kHz) produced by clicks that last from 50 ms to 128 ms.

echolocation the location of objects through the analysis of echoes, or reflected sound

Dolphins

Dolphins use nasal sacs to make high-frequency sounds. The sounds pass through the melon, which is an oval-shaped sac filled with special fats called acoustical lipids (**Figure 2**). The fats help the melon act like a lens for sound. From the melon, the sound is focused into a beam in front of the dolphin. When the sound waves reflect off an object in the water, such as a fish, the echo returns to the dolphin and provides the object's location. The dolphin receives the echo through its lower jaw. High-frequency waves do not travel far in water, so the range of echolocation is limited to between 5 m and 200 m for an object 5 cm to 15 cm in length.

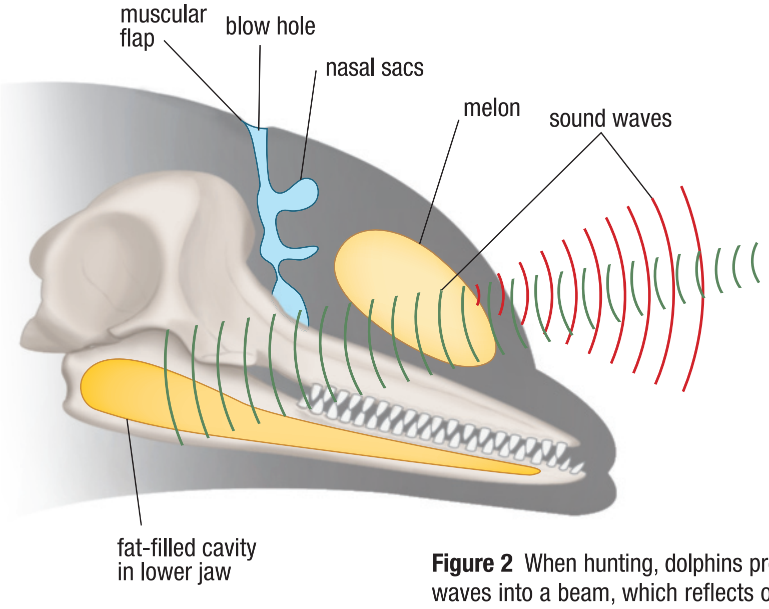


Figure 2 When hunting, dolphins produce high-frequency sound clicks. The melon directs the sound waves into a beam, which reflects off fish.

The fat-filled cavities in the lower jaw conduct the vibrations to the middle ear, which leads to the inner ear and then through the auditory nerve and to the brain. The dolphin brain receives these vibrations as nerve impulses, which it then interprets. Dolphins can detect the size, shape, speed, distance, and direction of objects. They can even detect information about the internal structure of objects. With experience, they can learn to recognize echoes from a preferred prey. Despite the many advantages of echolocation, research has shown that dolphins are much more effective hunters when they use sight with echolocation. Orca whales and sperm whales use a similar method to detect prey. The main difference is in the method of sound production and the frequencies of sound produced.

WEB **LINK**

To learn more about echolocation,

GO TO NELSON SCIENCE

Research This

Dolphin Echolocation and Detecting Underwater Mines

Skills: Researching, Analyzing, Evaluating, Communicating, Defending a Decision

SKILLS HANDBOOK A5.1

The U.S. Navy Marine Mammal Program trains dolphins and other marine animals to use their echolocation capabilities to detect underwater mines (**Figure 3**). In this activity, you will research this topic and form an opinion on whether or not dolphins should be used for this dangerous activity.

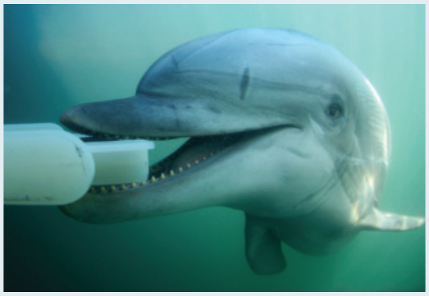


Figure 3 Dolphins are being trained to detect underwater mines.

1. How do dolphins detect the underwater mines?
2. How does using dolphins or other marine mammals for this activity help humans?
3. What advantages do dolphins have over humans to perform this activity?

A. Should we use any animals to perform dangerous tasks for us? T/I A

B. Form an opinion on the use of dolphins for this activity. T/I A

C. Organize your findings and your opinion in a format that is easily shared with your classmates. C A

GO TO NELSON SCIENCE

Bats

Bats use echolocation to navigate in complete darkness and detect the size, shape, and texture of objects such as insects when they are hunting. Bats produce sound in the larynx, and the sound passes out through the mouth. The frequencies of the sounds produced (up to 110 kHz) are often well above frequencies that humans can detect. A flap of skin in the bat's inner ear detects the sound.

While a bat is searching for prey, it produces sound at a rate of 10 to 20 pulses per second. To conserve energy, the bat breathes and beats its wings at the same frequency. When a bat detects prey, the bat heads toward the prey while producing high-frequency pulses, which can be as high as 200 pulses per second (**Figure 4**). As it approaches the target, the duration and loudness of the pulses decrease until the bat reaches the target. The bat then scoops the prey into its wing membranes and then into its mouth.

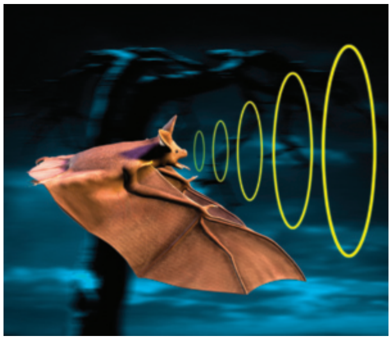


Figure 4 The yellow circles represent the high-frequency pulses that many bats emit. The pulses reflect off surrounding objects back to the bat's ears.

Elephants

Elephants have the largest brain of any land animal, and their behaviours demonstrate a high degree of intelligence. A large portion of their brain is devoted to hearing. Many people look at those large ears and think they understand how elephants can detect sound over large distances and find other elephants. Actually, the large pinnae have just as much to do with cooling the animals and other behaviours, such as displays of aggression as they defend their young from predators.

Unlike with humans, the ear is not the only detector of sound in elephants. Elephants also have hearing receptors in their trunks and feet. Elephants have been seen pressing their trunks against the ground when trying to detect sounds. They also lift up one foot to press the other three more firmly against the ground (**Figure 5**). Elephants do this because they send sounds through the ground as well as through the air. This low-frequency (infrasound) sound is produced at 15 Hz to 35 Hz and can be as loud as 117 dB. Typically, the sound travels much farther than higher frequencies, up to 10 km. The sound can be detected by the sensitive receptors in their feet and trunk. Some researchers think that the bottom of an elephant's foot actually resonates with these low frequencies like a drum.

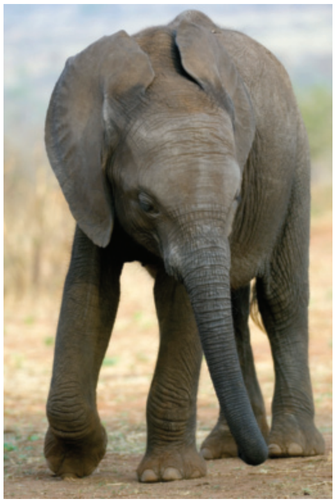


Figure 5 Elephants often lift one foot off the ground when listening to distant low-frequency sounds from other elephants.

House Cats

House cats have excellent hearing, among the best of any mammal. They can detect a wide range of frequencies, from 55 Hz to 79 kHz (higher than frequencies that both humans and dogs can detect). They also have large movable pinnae, which help amplify the sound and sense the direction from which the sound is coming (**Figure 6**). This is extremely helpful in hunting.

Cats can see in dim lighting conditions but, in doing so, sacrifice some detail and the perception of some colours. As a result, cat vision is poor up close. They often compensate for this by using their large pinnae to detect the high-pitched noises produced by their prey at the end of the hunt. These noises help locate the exact position of the prey up close when cat vision is poor.

Figure 6 Cats have large movable pinnae to amplify sound and detect the direction from which a sound is coming.

10.7 Summary

- Natural phenomena can be explained with reference to the characteristics and properties of sound waves.
- Dolphins, sperm whales, and orca whales use echolocation to navigate and detect prey in dark, murky waters.
- Bats also use echolocation to detect prey.
- Elephants produce infrasound waves, which travel partially through the ground. They can detect these sounds with their feet and trunks pressed against the ground.
- Cats use their large movable pinnae to amplify sound and to detect the direction from which sounds are coming.

10.7 Questions

1. Research the term "sonar." Echolocation is also called biosonar. Explain why this term is used for echolocation by comparing it to "sonar." Use diagrams in your answer. T/I C
2. The speed of sound in sea water is 1470 m/s. Using echolocation, a dolphin can detect small objects 5 m to 200 m away. Calculate the maximum and minimum times for the echo to return to the dolphin when detecting small objects. T/I
3. Echolocation only works well when the object is as long as or longer than one wavelength of the sound produced. K/U T/I
    (a) Why do you think bats need to use such high frequencies for echolocation?
    (b) Estimate the size of the smallest object a bat can detect using echolocation when the air temperature is 22 °C.
    (c) Explain why dolphins use high frequencies when hunting using echolocation.
4. Research an animal that uses echolocation. Create a table, like **Table 1**, and compare the echolocation of the animal you chose to dolphin and bat echolocation. T/I C

Table 1 Echolocation in Animals

Animal	Method of producing sound	Frequencies of sound used	Method of receiving sound	Information gained using echolocation
your animal				
dolphin				
bat				

5. Draw a neatly labelled diagram of an elephant showing why it can detect sound over large distances. K/U C
6. The Elephant Listening Project has done some innovative research on elephant communication and hearing. Research this organization, and summarize, in a format of your choice, what they have learned about elephant language and hearing. T/I C
7. Explain why you think elephants hold their ears out wide when listening to sounds. T/I
8. List three hearing advantages that (a) elephants and (b) house cats have over humans in terms of hearing ability. K/U

GO TO NELSON SCIENCE

CHAPTER 10 Investigations

Investigation 10.1.1 OBSERVATIONAL STUDY

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Investigating Frequency, Loudness, and Human Hearing

According to the 1990 Occupational Health and Safety Act, exposure to any sound level above 85 dB for an 8 h period is considered unsafe. Also, for every 3 dB of loudness above 85 dB, the time of exposure should be cut in half. For example, exposure to a noise level of 91 dB should be 2 h or less.

In this activity, you will test the range of human hearing in your class in terms of the range of frequency and loudness that everyone can detect. You will also test different areas in the school for loudness to determine whether these sound levels are safe.

Note: Anyone with a hearing impairment may choose not to participate in this study, according to their individual comfort level.

If you use a hearing aid, tell your teacher, and ask to be excused from the room if you feel the noise or sound level is hurting you.

Purpose

- To determine the range of human hearing in your class in terms of frequency and loudness
- To determine if the loudness levels in different areas of the school are safe

Equipment and Materials

- sound-generating equipment
- sound-level meter

Procedure

SKILLS HANDBOOK A2.4

Part A: Frequency and Loudness

1. Your teacher will use sound-generating equipment to produce sound at a level and frequency that everyone can detect. When everyone in the class, including the teacher, can hear the sound, they should raise their right hand.
2. Your teacher will gradually lower the frequency of the sound while reading off the frequencies. When you can no longer hear the sound, put your hand down.
3. Repeat the procedure for higher frequencies.
4. Repeat the procedure for decreasing loudness.

Part B: School Sound Levels

5. Using the sound meter, measure the sound level in one part of the school. Suggestions are the music room during a band practice and the cafeteria at lunchtime. Try to get minimum, maximum, and average sound levels over a 15 min interval for each area you test.

Analyze and Evaluate

(a) What variables were measured or manipulated in this study? What type of relationship was being tested? T/I

(b) What range of frequencies can you detect? How does this range compare with your teacher's range and the widest range for the class? T/I

Apply and Extend

(c) The lowest loudness detected by a person also depends on the frequency of the sound. How could you determine which frequencies you are most sensitive to? T/I

(d) When testing loudness, you only determined the lower range of loudness, not the upper range. Explain why. T/I

(e) What is the lowest sound level you can detect? How does this level compare with your teacher's level and that of the class? T/I

(f) What is the average sound level detected in the area you tested? Is the sound level safe in this area? Explain your answer. T/I

Investigation 10.2.1 OBSERVATIONAL STUDY

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Waveforms of Instruments

In this activity, you will view the waveforms generated by a tuning fork and three types of musical instrument: a stringed instrument (for example, a sonometer or an acoustic guitar), a percussion instrument, and a wind instrument. You will look for differences in these waveforms and attempt to identify which harmonics are involved.

Purpose

To determine how the waveforms produced by a tuning fork and by musical instruments differ

Equipment and Materials

- microphone
- amplifier and oscilloscope or computer
- tuning forks with different frequencies
- rubber hammer
- stringed instrument
- percussion instrument
- wind instrument

Procedure

SKILLS HANDBOOK A2.4

1. In front of the microphone tap a tuning fork with a rubber hammer at various positions along the length of the tine, while watching the waves on the oscilloscope. Sketch the resulting waveform. Test the effect of the following on the waveform produced:
   (a) tapping the tuning fork harder
   (b) using different frequencies of tuning fork
2. Pluck the string on the stringed instrument in the middle, and sketch the resulting waveform. Pluck the string at two or three other places, and observe the effect on the resulting waveform. Sketch each new waveform.
3. Sound the percussion instrument, and sketch the resulting waveform. Try to produce different waveforms by striking the instrument in different positions. Sketch each new waveform.
4. Sound the wind instrument, and sketch the resulting waveform. Try producing different sounds, and observe the effect on the resulting waveform. Sketch each new waveform.

Analyze and Evaluate

(a) What happened to the quality of the fundamental frequency when you changed the tapping position on the tine of the tuning fork? T/I

(b) What effect did each of the following have on the waveform produced: T/I

(i) tapping the tuning fork harder

(ii) using different frequencies of tuning fork

(c) What happened to the resulting waveforms and number of harmonics produced when the plucking position on the string was moved away from the middle? T/I

(d) What effect did different striking positions have on the waveform produced by the percussion instrument? T/I

(e) Describe the effect on the waveforms produced by the wind instrument when producing different sounds. T/I C

Apply and Extend

(f) Describe how this method of displaying sound could help a sound engineer analyze the quality of sound from a musical instrument. A

(g) The quality of sound produced by the tuning fork is poor compared to the sound produced by most musical instruments. Predict what will happen to the quality of sound produced by the tuning fork if it is mounted on top of a box that is closed at one end. Explain your reasoning, then test your prediction. T/I C

(h) Briefly explain how to identify the different sounds produced by a tuning fork and the three instruments. T/I

Investigation 10.3.1 OBSERVATIONAL STUDY

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Investigating Acoustic Surfaces

In this activity, you will design a soundproof box that can be used to reduce the loudness of a sound source. The objective is to build an effective soundproof box that will limit the amount of sound coming out of the box as much as possible, while keeping the box as light and small as possible. Much of the design of the soundproof box is up to you, but your teacher will provide you with some limitations. For example, everyone will use the same type of sound source, the box must be able to accommodate the source of the sound, it should have an upper limit on size and mass, it must be easy to open and close, and it has to be a box.

You will rate your design by calculating a score. To determine your score, you will divide the highest sound reading immediately outside the box, at any location, by the product of the volume and mass of the box. Your teacher might require you to do most of the construction and testing at home, so keep a log of the ideas and methods you used to build the box.

Purpose

To determine the best design for a soundproof box

Equipment and Materials

- sound source, such as an alarm clock, bell, or buzzer
- various materials to build a soundproof box
- sound meter
- mass balance
- metre stick

Procedure

SKILLS HANDBOOK A2.4

1. Design a prototype for your box. Have your design approved by your teacher.
2. Once your design has been approved, build the prototype.
3. Test the box and calculate your score. Look for ways to improve your score, and test these ideas. Record any scores and improvements in your log.
4. Test your box again. On the due date, test it again in front of your teacher using the method that produces the best score. Calculate this score, and hand in the calculations to your teacher.

Analyze and Evaluate

(a) What variables did you measure in this investigation? T/I

(b) List the materials you used as well as your reason(s) for using them. T/I

(c) What two design features of the box helped to increase the score the most? T/I

(d) Why was the sound level of the box tested at several locations outside the box? T/I

(e) Describe why the method used to calculate the score is fair. Is there anything about this method that is unfair? Explain your reasoning. T/I

Apply and Extend

(f) Describe one application of this soundproof box that could be used in industry. Would you change any design features to accommodate this application? Explain your answer. A

(g) Would you expect the score of the box to vary with different frequencies of sound? How would you test the box to determine how effective it is with a range of different frequencies? T/I

CHAPTER 10 SUMMARY

Summary Questions

1. Create a study guide based on the points in the margin on page 448. For each point, create three or four subpoints that provide further information, examples, explanatory diagrams, or general equations.
2. Look back at the Starting Points questions on page 448. Answer these questions using what you have learned in this chapter. Compare your latest answers with those that you wrote at the beginning of the chapter. Note how your answers have changed.

Vocabulary

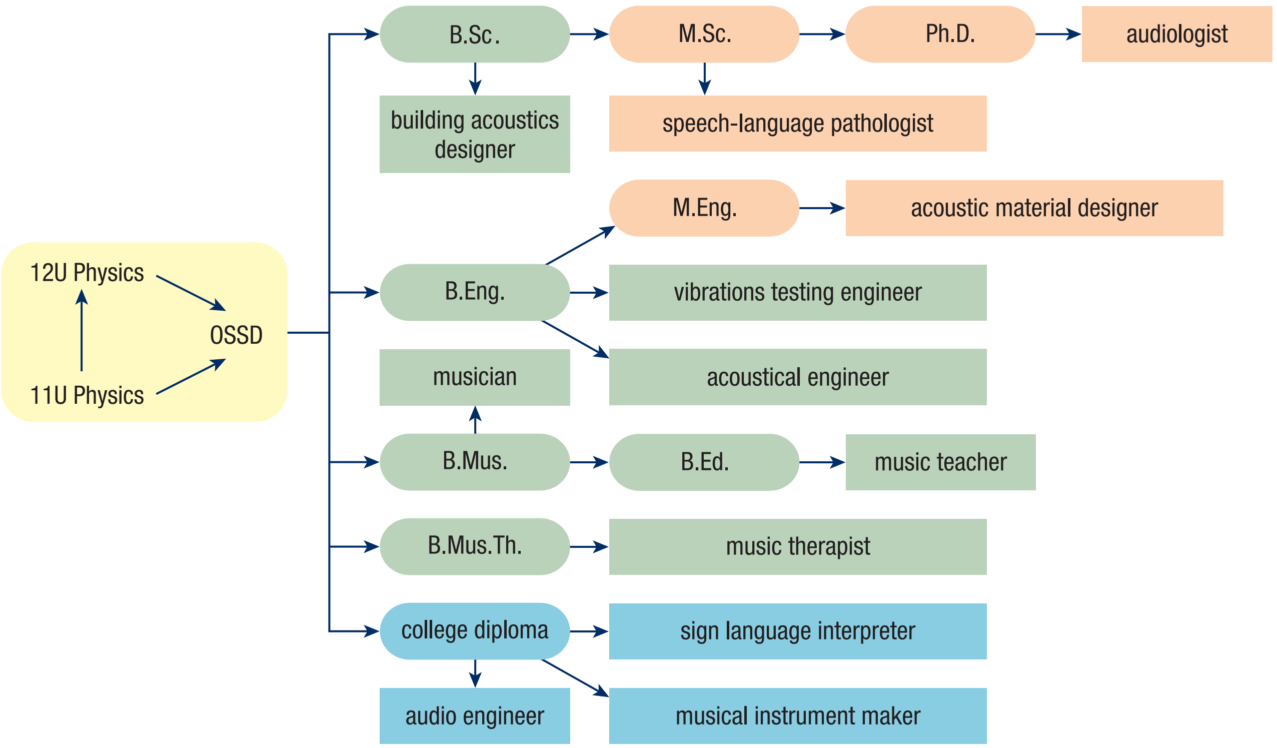
music (p. 454)
noise (p. 454)
pitch (p. 454)
quality (p. 454)
resonator (p. 455)
building acoustics (p. 461)
reverberation time (p. 461)
mechanical resonance (p. 464)
sympathetic vibration (p. 464)
aeroelastic flutter (p. 464)
tsunami (p. 466)
seismic waves (p. 466)
echolocation (p. 472)

CAREER **PATHWAYS**

SKILLS HANDBOOK A7

Grade 11 Physics can lead to a wide range of careers. Some require a college diploma or a B.Sc. degree. Others require specialized or postgraduate degrees. This graphic organizer shows pathways to a few careers related to topics covered in this chapter.

1. Choose two of the careers listed in this chapter that interest you, or choose two other careers that relate to Applications of Waves. For each of these careers, research the educational requirements, skill/personality/aptitude requirements, and potential employers, salary, and duties and responsibilities.
2. Assemble the information you have discovered into a brochure. Your brochure should compare and contrast your two chosen careers and explain how they connect to Applications of Waves.


12U Physics
11U Physics
OSSD
B.Sc.
M.Sc.
Ph.D.
audiologist
building acoustics designer
speech-language pathologist
M.Eng.
acoustic material designer
B.Eng.
vibrations testing engineer
acoustical engineer
musician
B.Mus.
B.Ed.
music teacher
B.Mus.Th.
music therapist
college diploma
sign language interpreter
audio engineer
musical instrument maker

GO TO NELSON SCIENCE

CHAPTER 10 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. Although the ear is known as the detector of sound, which organ has more to do with hearing than the ear? (10.1) K/U
   (a) the nose
   (b) the brain
   (c) the tongue
   (d) the esophagus
2. The quality of a musical sound depends on the
   (a) number and intensity of the antinodes
   (b) number and intensity of the nodes
   (c) number and intensity of the harmonics
   (d) The quality of a musical sound cannot be determined. (10.2) K/U
3. Which type of percussion instrument is the kettle drum? (10.2) K/U
   (a) single indefinite pitch
   (b) multiple definite pitch
   (c) variable pitch
   (d) none of the above
4. Reverberation time is the time for the sound to drop by 60 dB from its maximum loudness or
   (a) five minutes, whichever is longer
   (b) to drop to an inaudible level
   (c) to increase by 5 dB
   (d) the length of time of four echoes (10.3) K/U
5. With aeroelastic flutter, what is the relation between energy added to and lost from a vibrating structure? (10.4) K/U
   (a) Energy loss is less than energy added.
   (b) Energy loss is equal to energy added.
   (c) Energy loss is greater than energy added.
   (d) There is not enough information to compare.
6. Which of the following is a wave of energy that travels through Earth? (10.5) K/U
   (a) tsunami
   (b) tidal wave
   (c) rogue wave
   (d) seismic wave
7. Which of the following is defined as an interruption of airflow? (10.6) K/U
   (a) engine vibration
   (b) aerodynamic brakes
   (c) flutter
   (d) buffet
8. An abnormal vibration in a plane can result in which of the following dangerous effects? (10.6) K/U
   (a) pogo effect
   (b) turbulence
   (c) flutter
   (d) engine noise
9. When prey is close, cats use their hearing to make up for which sense? (10.7) K/U
   (a) sight
   (b) smell
   (c) touch
   (d) taste

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

10. The Eustachian tube only opens when you swallow. (10.1) K/U
11. The pinna channels the sound waves into the auditory canal toward the middle ear. (10.1) K/U
12. Music is sound that originates from a combination of musical notes, which originate from a source that vibrates in a uniform manner with one or more constant frequencies. (10.2) K/U
13. Substances with larger absorption coefficients have longer reverberation times. (10.3) K/U
14. Brick has a shorter reverberation time than fibreglass. (10.3) K/U
15. Sympathetic vibration is the response to a vibration with the same aeroelastic flutter. (10.4) K/U
16. In a vibrating structure such as a skyscraper, dampers inside the structure take energy from the building when it vibrates, thus increasing the amplitude of vibration. (10.4) K/U
17. P-waves move at almost half the speed of S-waves. (10.5) K/U
18. Aircraft flight crews do not get used to normal vibrations. (10.6) K/U
19. Longitudinal vibrations in a rocket are called the pogo effect. (10.6) K/U
20. Natural phenomena cannot be explained with reference to the characteristics and properties of sound waves. (10.7) K/U

To do an online self-quiz,
GO TO NELSON SCIENCE

CHAPTER 10 REVIEW

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

Knowledge

For each question, select the best answer from the four alternatives.

1. The auditory canal is part of the external ear along with the
   - (a) tympanic membrane
   - (b) Eustachian tube
   - (c) cochlea
   - (d) pinna (10.1) K/U
2. What is the more common name for the ear's tympanic membrane? (10.1) K/U
   - (a) earlobe
   - (b) stirrup
   - (c) eardrum
   - (d) cochlea
3. Noise is a sound that originates from a source that vibrates
   - (a) with a high amplitude
   - (b) in an out-of-control fashion
   - (c) in a random manner
   - (d) in a uniform manner (10.2) K/U
4. Building acoustics are defined as the total effect of sound produced
   - (a) in an enclosed or restricted space
   - (b) by a building's mechanical system
   - (c) in an open or unrestricted space
   - (d) within a specified distance from a building (10.3) K/U
5. Refer to **Table 1**. Which of the following materials would be best suited as a surface in a room in which the most important requirement is short reverberation time? (10.3) K/U
   - (a) pine
   - (b) concrete
   - (c) fibreglass
   - (d) brick

Table 1 Sound Absorption Coefficients for Various Materials

Substance	At 512 Hz	At 2048 Hz
pine	0.06	0.10
concrete	0.025	0.035
fibreglass	0.99	0.86
brick	0.03	0.049

6. Mechanical resonance is a type of energy transfer resulting from two objects that share the same
   - (a) mass
   - (b) amplitude
   - (c) length
   - (d) natural frequency (10.4) K/U
7. A series of enormous sea waves caused by an earthquake or other disturbance is a
   - (a) tidal wave
   - (b) cyclone
   - (c) hurricane
   - (d) tsunami (10.5) K/U
8. The most dangerous type of aircraft vibration is
   - (a) aeroelastic flutter
   - (b) engine noise
   - (c) buffet vibration
   - (d) vibration felt during landings (10.6) K/U
9. The function of acoustical lipids in a dolphin is
   - (a) to protect the nasal sacs from sound frequencies that are too high
   - (b) to help the melon act like a lens for sound
   - (c) to protect the muscular flap
   - (d) to supply additional nourishment for the dolphin when food is scarce (10.7) K/U

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

10. Damage to the eardrum can be repaired with surgery, as can damage to hairs in the cochlea. (10.1) K/U
11. An air column that is closed at one end has higher harmonics that are odd-number multiples of the fundamental frequency. (10.2) K/U
12. Vibrations caused by extension and retraction of landing gear and the deployment of aerodynamic brakes are unusual and dangerous. (10.6) K/U
13. Animals that use echolocation use a variety of frequencies in the range 20 Hz to 20 kHz. (10.7) K/U

Match each term on the left with the most appropriate description on the right.

14. (a) stringed instruments (i) striking a surface
    (b) wind instruments (ii) plucking, striking, or bowing
    (c) percussion instruments (iii) vibrating columns of air molecules (10.2) K/U

Write a short answer to each question.

15. In the auditory canal, what frequency range is magnified by a factor of about ten? (10.1) K/U
16. The eardrum is what separates the outer ear from which part of the ear? (10.1) K/U
17. Define music. (10.2) K/U
18. What is it about musical loudness, pitch, and quality that make them subjective characteristics? (10.2) K/U
19. What is the purpose of the resonator of a stringed instrument? (10.2) K/U
20. Explain why a piano, which is classified as a stringed instrument, could also be classified as a percussion instrument. (10.2) K/U C
21. Define reverberation time. (10.3) K/U
22. Does your singing really sound better in the shower? Explain your answer. (10.3) T/I
23. Define aeroelastic flutter. (10.4) K/U
24. Why do some tall buildings have a concrete or steel pendulum installed in them? (10.4) K/U
25. Define echolocation. (10.7) K/U
26. Aside from the ears, name two locations of hearing receptors in elephants. (10.7) K/U

Understanding

27. In a graphic organizer such as a flow chart, show how the human ear detects sound. (10.1) K/U C
28. In many environments, it is difficult to understand conversations because of background noise. How does the fact that the highest note attainable by the average voice is approximately 1000 Hz help explain conversations being so easily overpowered? (10.1) K/U
29. Describe what happens to cause temporary hearing loss during a sinus infection. (10.1) K/U
30. (a) Name the bones that transmit sounds from the eardrum to the cochlea.
    (b) Describe how these bones act together to transmit sound.
    (c) In which part of the ear are these bones located? (10.1) K/U
31. Explain how the brain uses cochlear hairs to translate mechanical vibrations into a determination of the frequency and loudness of a sound. (10.1) K/U
32. Explain the difference between the objective amplitude of a sound wave and its subjective loudness. How does someone who is unable to detect specific frequency ranges detect this difference? (10.2) K/U
33. What is the difference between the sound produced by a tuning fork and that produced by most other musical instruments? (10.2) K/U
34. Identify the three types of musical instruments, and explain the source of the vibration that causes each to produce sound. (10.2) K/U
35. A string of length 1.25 m is plucked in the middle, producing an antinode at the fundamental frequency. What is the wavelength of the vibration in the string? (10.2) K/U
36. A violin string is vibrating as shown in **Figure 1**.

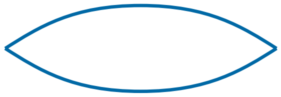


Figure 1

    (a) What is the length of the violin string if its wavelength is 0.656 m?
    (b) The same string vibrates with a fundamental frequency of 293 Hz. If the player decreases the string's length to 0.287 m by pressing the string, what is the new frequency? (10.2) K/U
37. A 0.875 m piece of wire is held tight between two points. When the wire is plucked, the frequency of the sound created is 3650 Hz. The wire is then shortened to create a 4260 Hz sound. What is the new length of the wire? (10.2) K/U
38. (a) A guitar's string is 64.8 cm long. What is the fundamental frequency of this string if its wave speed is 190.2 m/s?
    (b) What is the wavelength?
    (c) The other strings on the guitar are the same length but have higher fundamental frequencies. What differences between these strings and the string in (a) might exist to create the difference in fundamental frequencies? (10.2) K/U T/I

39. A trombone player extends the slide on the trombone to extend the length of the air column (**Figure 2**). A change in the air column produces a change in the frequency. (10.2) K/U

Figure 2

(a) What effect does extending the trombone slide have on the sound produced?
(b) What effect does retracting the trombone slide have on the sound produced?

40. Describe the different methods of producing a sound with each of the following instruments: a flute, a clarinet, and a trumpet. (10.2) K/U

41. Explain how the nominal note heard by a wind instrument is determined and what will increase the quality of sound of that note. (10.2) K/U

42. Percussion instruments can be grouped into three categories. Identify each category, describe what type of sound that category creates, and suggest how it might be used in a musical composition. (10.2) K/U C

43. A concert hall has a reverberation time of 3.0 s, which is longer than needed. What could be done to reduce the reverberation time? (10.3) K/U

44. (a) Explain why it is difficult to design a single room that acts as a venue for both choral music and speaking engagements.
    (b) Which requires a longer reverberation time—a venue for choral music or a venue for speaking engagements? (10.3) K/U

45. Explain the difficulties that arise acoustically when surfaces within a space are either concave or convex in shape. (10.3) K/U

46. (a) Describe the following spaces: a live room, an intimate room, and a full room.
    (b) Can a room be both live and intimate? Explain your answer.
    (c) Can a room be both intimate and full? Explain your answer.
    (d) Can an anechoic chamber be a full room? Explain your answer. (10.3) K/U

47. Describe two methods of reducing vibration in skyscrapers, and explain how each decreases the risk of a structure experiencing aeroelastic flutter. (10.4) K/U

48. In a Venn diagram, compare P-waves and S-waves in terms of wave type and speed. (10.5) K/U C

49. Discuss how geophones are used to determine the nature of materials deep underground. (10.5) K/U C

50. Identify whether P-waves or S-waves are being illustrated in **Figure 3**. (10.5) K/U

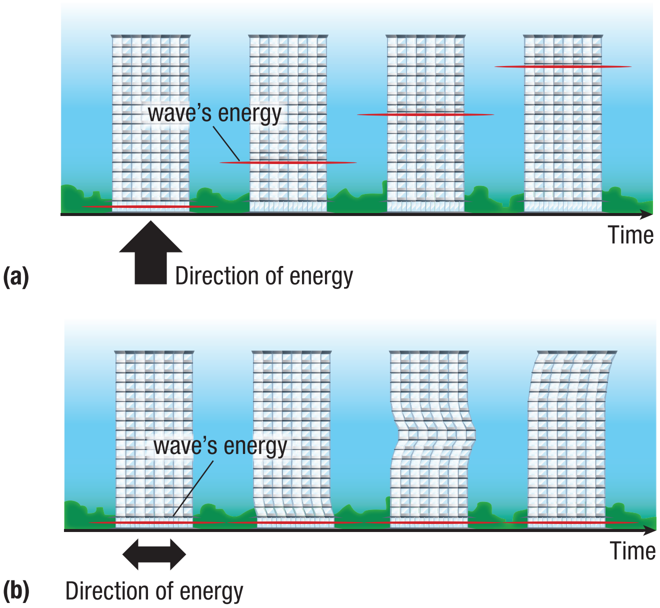


Figure 3

51. (a) Describe how a pulse test is performed on an aircraft. What phenomenon is it used to identify?
    (b) Describe how a sweep test is performed on an aircraft. What phenomenon is it used to identify? (10.6) K/U

52. Explain what precautions engineers take against the pogo effect in rockets. (10.6) K/U

53. Various animals use echolocation as a tool for hunting and navigation. (10.7) K/U
    (a) Describe the process of echolocation used by dolphins.
    (b) Describe the process a bat uses to hunt small prey.

Analysis and Application

54. Why do you think that people who are sensitive to cabin pressure changes in aircraft should chew gum during takeoff and landing? (10.1) T/I A

55. The human ear canal is about 2.8 cm long. If it is regarded as a tube that is open at one end and closed at the eardrum, what is the fundamental frequency around which we would expect hearing to be most sensitive? Take the speed of sound to be 340 m/s. (10.1, 10.2) T/I A

56. Guitar manufacturers allow for predefined changes of string length by adding frets. **Figure 4** shows a guitar string and each note created by pressing the string at each fret.

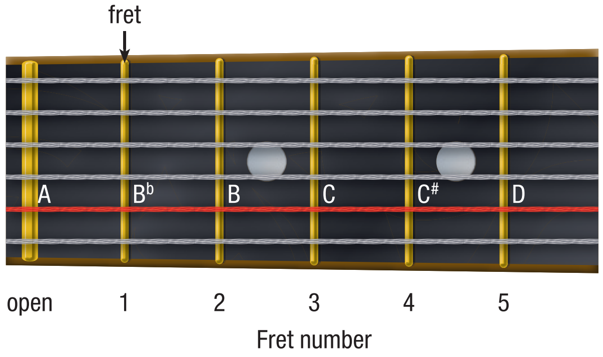


Figure 4

Table 2 shows the correlation between note, frequency, and string length. Copy Table 2 into your notebook and complete it using Figure 4. (10.2) A

Table 2 Guitar Notes, String Length, and Frequencies

Note	Fret number	Frequency (Hz)	Length (m)
A	open	111	0.642
B^b			0.609
B	2	123	
C		131	
C$^\#$			0.513
D	5		0.485

57. A guitar string has a frequency of 172 Hz and a length of 59.1 cm. (10.2) T/I A
    (a) A guitarist reduces the string's length by 13.2 cm by pressing on the string. What is the new frequency?
    (b) How would the frequency from (a) be affected if by pressing down on the string, the guitarist also slightly increased the tension on the string?
    (c) Assuming the frequency from (a) is the desired frequency for proper tuning, what might a guitar manufacturer do with respect to placement of the notes on the guitar's fret board to counteract this slight tension increase?

58. As the musicians in an orchestra warm up, the frequencies of the wind instruments rise and the frequencies of the string instruments fall. Explain why. (10.2) A

59. The equations for vibrating strings you learned in this chapter can be combined in useful ways with those you learned in Chapter 8. (10.2, 10.3, 10.4) K/U T/I A
    (a) Using equations from Chapter 8, write an equation for the frequency, f, of a vibrating string in terms of tension, F_T; linear density, μ; and length, L.
    (b) Rearrange the equation from (a), and write an equation for tension, F_T, in terms of frequency, f; mass, m; and length, L.
    (c) Use your equation from (a). A string with a tension of 340 N and a linear density of 0.0036 kg/m vibrates at a frequency of 640 Hz. What is the length of this string?
    (d) Shortening the string in (c) to what length will result in the vibration's frequency increasing to 830 Hz?
    (e) Use your equation from (b). A violin's 0.33 m long string has a fundamental frequency of 440 Hz when tightened to 220 N of tension. What is the mass of this string?

60. Find a space in which you can demonstrate to yourself that the reverberation time is relatively high. (10.3) T/I A
    (a) Identify the space, and describe what process you used to make this determination.
    (b) Describe the characteristics of the space, including materials of the space and aspects such as whether the space is small or large, open or enclosed, and so on.

61. Explain the difference between mechanical resonance and aeroelastic flutter. Describe a case that proves that they are not mutually exclusive. (10.4) K/U

62. Using your knowledge of the Tacoma Narrows Bridge collapse, explain the necessity of reducing the occurrence of aeroelastic flutter in aircraft. (10.6) K/U

63. (a) Compare the clicks produced by dolphins, sperm whales, and orca whales for echolocation purposes to the range of sounds detectable by humans.
    (b) What does the range of frequencies used by an animal for echolocation suggest about its relationship to the object being located? (10.7) T/I A

Evaluation

64. Given the challenge faced by acoustical engineers to design spaces that serve as multifunctional venues, one solution is to temporarily change the acoustical properties of the space to most appropriately match the requirements of the current use. Suppose there is an empty room with wooden seating, designed to hold concerts. This room will be temporarily used for a speaking engagement. Propose at least three temporary design elements that could be added to the empty room. Does each design element increase or decrease the reverberation time of the room's acoustics? (10.3) T/I A

65. A challenge faced by acoustical engineers is the difference in acoustical properties of a full auditorium compared with a nearly empty auditorium. (10.3) T/I
    (a) What design adjustments could be taken into consideration to make these two scenarios as acoustically equivalent as possible?
    (b) What design choices should be avoided?

66. The auditorium shown in **Figure 5** is being investigated by acoustical engineers because there have been complaints about its performance as a speaking space. The seating area is between two rows of round concrete columns. Curved brick walls sit behind both the presentation area and the seating area. The remaining walls are made of concrete, and the floor is marble with carpeted walkways. (10.3) T/I C

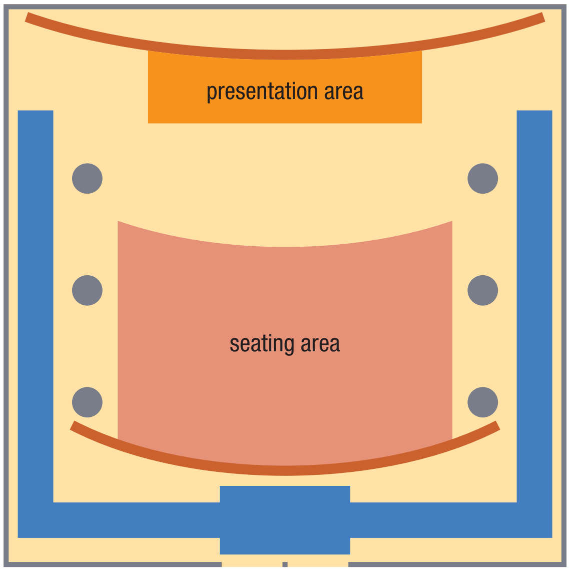


Figure 5

    (a) Evaluate the design of the auditorium. Modify at least five items that would make the room better for speaking engagements.
    (b) Draw a diagram of the new room, and describe how each change made will increase the sound quality of the space.

67. A car with an unbalanced wheel can experience mechanical resonance when the wheel spins at the natural frequency of the car. Knowing that mechanical resonance can be dangerous, what can the car driver do when vibrations begin? How will this stop the mechanical resonance? (10.4) T/I A

68. Two tall buildings are connected by a footbridge halfway up the buildings, similar to the one in **Figure 6**. Evaluate such a design. Is it risky or beneficial to have both buildings and the footbridge constructed such that they all have the same natural frequency? Explain your answer. (10.4) T/I C

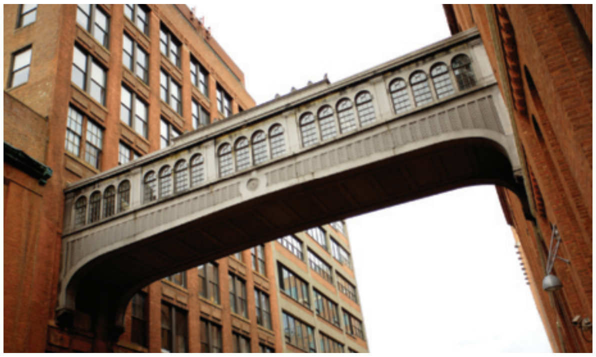


Figure 6

69. Sweep tests and pulse tests are both performed on an aircraft to predict its aeroelastic flutter characteristics. (10.6) C A
    (a) Which of these tests seems like the safer of the two? Defend your position.
    (b) Which test is more likely to identify possible flutter-inducing scenarios? What about this test makes flutter detection more likely?

Reflect on Your Learning

70. Now that you have studied the mechanism of human hearing, what changes can you make in your behaviour to protect yourself from hearing loss? Does knowing that the parts of your ear are very small and fragile make you more or less likely to take hearing protection more seriously than you would have before learning this information? T/I C A

71. Designing for acoustics and waves is something that many people remain unaware of until a problem arises based on a poor design. Now that you are aware of how much effort is taken to reduce the impact of waves on everything from buildings to airplanes, how might you use this knowledge to make informed decisions in your daily life? Discuss issues that might arise from such situations as decorating a space at home or selecting a product to purchase and how to avoid them by applying your understanding of wave physics. T/I C A

72. How has your understanding of the use of sound in the animal kingdom changed after having studied this chapter? Was your understanding of this subject limited to human uses of sound, for example, communication and warnings of danger? T/I C

Research

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73. Hearing loss devices are being developed to help more people with hearing loss than ever before. Research the development of hearing loss technology. Write a report that describes the origins of modern hearing aids. In your report, discuss major developments through newer technology, including innovations such as cochlear implants and Baha hearing aids. When helpful, provide diagrams to illustrate each technology's application. K/U T/I C

74. Seismic geophysical exploration has become the most important form of geophysical exploration used today. However, many other methods exist that have the same goal as geophysical exploration. Select a type of nonseismic geophysical exploration, for example, magnetic, gravity, electrical, radioactive, or well logging. Research the method, and prepare a graphic organizer that compares how it works, its advantages, and its disadvantages with seismic geophysical exploration. Consider these questions: What materials is it able to detect? What are its limitations? What are the associated costs? What is this method's greatest strength? K/U T/I C A

75. "Noise music" is an oxymoron. An oxymoron is a figure of speech in which contradictory terms appear next to each other. The term "noise music" has been adopted by practitioners of a specific strain of a musical composition with a nontraditional attitude toward tonality, rhythm, and many other concepts that define music as most of us know it. Research noise music. Prepare a web page or a blog, with audio links if possible, indicating your opinion on whether this genre counts as music or noise. Defend your position. K/U T/I C

76. Music synthesizers create waveforms with frequencies that can register to the ear as music but are not of as high quality as the music produced by an acoustical instrument. As discussed in this chapter, however, much of the quality of a musical note is determined by the complexity of the relationship between the fundamental frequency and the harmonic overtones present in the musical tone. Research the relationship between fundamental frequencies and their harmonics. Discuss this relationship in a short report. Use this understanding to develop an explanation of how different musical instruments sound different from each other. T/I C

77. Many of the world's worst natural disasters have been caused by seismic activity. Tsunamis and earthquakes have caused untold amounts of damage throughout history. Research a major seismic disaster and prepare a visual presentation. Include the location of, magnitude of, and damage created by this disaster. If possible, identify the geographic area that was affected, and discuss whether any preventive actions were taken to prevent casualties or damage. K/U T/I C

78. The organs that produce the most complex sounds in the animal kingdom are the human vocal folds, or vocal cords. Research human vocal folds, and describe how they are structured and how they create sound. T/I C

79. The magnitude of an earthquake is determined using the Richter magnitude scale. Research the Richter scale. Write a report detailing, among any other interesting findings, a brief history of the Richter scale, the relationship between the values of the Richter scale, and the meaning of the values in terms of the effect an earthquake of a given size has on people and property. K/U C

80. Engineers must design structures to minimize the effects of resonance. In order to test their plans, designers often use models such as earthquake shaking tables. T/I C A
    (a) Research how to construct an earthquake shaking table.
    (b) Design an experimental procedure to determine resonant frequencies for a tower constructed from Popsicle sticks or from light building blocks. If possible, build an earthquake shaking table and tower and do a demonstration.

81. Some people with poor or no eyesight have developed various degrees of echolocation ability. Research human echolocation, and write a report on your findings. Include a comparison of the ability of humans with echolocation skills to those same skills found in the animal kingdom. T/I C A

82. Research lobster sounds' natural frequencies. Prepare a visual presentation on how lobsters produce and use vibrations. Explain why lobster vibrations are said to be like a violin's vibrations. T/I C A

Applying Waves and Sound to Design

In this unit, you learned about several different structures, technologies, and devices that apply the properties of waves and sound. Some applications minimize the effects of waves to keep bridges and large buildings stable. Others use the properties of waves and sound in medical applications, such as ultrasound technology (**Figure 1**), or to produce sound, such as musical instruments. Many future applications will use the properties of waves and sound in new and innovative ways.

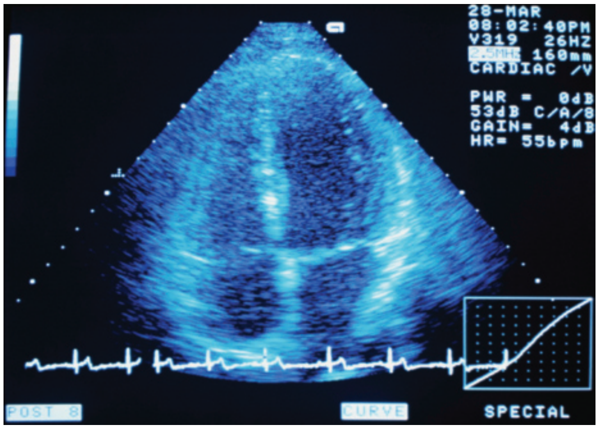

Figure 1 This ultrasound image shows the four chambers of a human heart.

There are two suggested tasks for this unit. Your teacher may assign one or have you choose one.

Option 1: Research a Structure or a Technology

As a group, research how the properties of mechanical waves and sound have influenced the design of a particular structure or technological device. You could research a structure or device already mentioned in the text or a new one. Suggestions are the design of bridges or buildings; the acoustical design of concert halls; and applications such as headphones, hearing aids, a musical instrument, wave pools, and tidal energy. In your research, include societal implications, such as noise pollution and hearing loss. Your research must contain new information and applications beyond those already studied in this unit. With your research, you will create a visually appealing, informative, and entertaining poster or electronic slide presentation.

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Option 2: Design and Construct a Device

As a group, design and construct a device that uses several concepts related to waves and/or sound, is safe, and meets one of the following criteria:

(a) The device demonstrates characteristics of waves or sound in an innovative way. The demonstration(s) can involve different types of waves as well as the properties of waves (for example, wavelength, frequency, and amplitude). Concepts such as wave speed, the Doppler effect, standing waves, and resonance could also be included. The device could serve as a teaching aid for a physics class.

(b) The device performs a task using the properties of waves and/or sound; for example, moving an object, triggering an event or series of events, keeping time, or creating sound or music.

(c) The device is a visually appealing, creative piece of kinetic art that involves in its operation the properties of waves and/or sound. You could partner with an art or design technology class. The art may or may not produce pleasant sounds, but it must demonstrate several properties of waves and/or sound.

Purpose

SKILLS HANDBOOK A5.1

- To create a poster or electronic slide presentation that shows how the properties of mechanical waves and sound have influenced the design of a structure or technology (Option 1)
- To design and construct a device that uses several properties of waves and/or sound (Option 2)

Equipment and Materials

Option 2

Many different materials can be used for this task. You can probably find some materials at home; you may be able to get other materials from your teacher.

Procedure

Option 2

1. Decide which device you will construct.
2. As a group, decide the main ideas or tasks for your device.
3. Draw a simple sketch of the device that clearly shows how it will look or work and which properties of waves and/or sound the device will apply.

4. Keep the materials and the size of the device reasonable. The device should fit comfortably on a science classroom desk. Create a materials list.

Ensure that your materials, tools, and final product are safe to use.

5. Prepare a report or summary of your design for approval by your teacher. In your summary, describe in detail the physics principles you are using and the expected performance of your device based on those principles. Note any suggestions from your teacher, and make appropriate changes to the design. Have the modified design approved by your teacher.
6. Construct the device, making notes of any design changes or difficulties in a log. Include diagrams in your log when necessary.
7. Demonstrate the device in the classroom, and be prepared to answer questions about how it applies the physics principles related to waves and/or sound.

Analyze and Evaluate

Option 1

(a) How does the structure or technology apply properties of waves and/or sound?
(b) What are the main uses of the structure or technology? Who uses it?
(c) What positive impact does the structure or technology have on society? Are there any negative impacts?
(d) What careers are involved with producing and maintaining the structure or technology?
(e) What new research is being done to improve these types of structures or technologies?

Option 2

(a) Which physics principles related to waves and/or sound does your device apply?
(b) How did your group test and improve your device?
(c) Describe in detail how your device works.
(d) How have the design and construction of your device improved your understanding of the physics principles related to waves and/or sound?
(e) What would you do differently if you built another device for a similar task?

ASSESSMENT **CHECKLIST**

Your completed Unit Task will be assessed according to these criteria:

Option 1

Knowledge/Understanding

- ✓ Demonstrate knowledge of different types of waves, as well as terminology associated with waves and sound.
- ✓ Demonstrate knowledge of technologies that apply principles and concepts related to waves and sound.
- ✓ Describe the impact of waves and/or sound on society and the environment.
- ✓ Demonstrate an understanding of the physics principles behind the structure or technology, as well as the wave equation, standing waves, and resonance.

Thinking/Investigation

- ✓ Research how the design of a structure or technology has been influenced by waves and/or sound.
- ✓ Create a poster or electronic slide presentation on a structure or technology involving waves and/or sound.

Communication

- ✓ Synthesize findings in the form of a poster or electronic slide presentation.
- ✓ Communicate recommendations clearly and concisely.

Application

- ✓ Identify careers associated with the structure or technology.
- ✓ Provide current research on the structure or technology.

Option 2

Knowledge/Understanding

- ✓ Demonstrate knowledge of different types of waves, as well as terminology associated with waves and sound.
- ✓ Demonstrate knowledge of technologies that apply principles and concepts related to waves and sound, as well as the wave equation, standing waves, and resonance.

Thinking/Investigation

- ✓ Design a device according to given specifications.
- ✓ Evaluate the design and modify it to improve performance.

Communication

- ✓ Prepare a log of the design and modifications.
- ✓ Demonstrate an understanding of the design of the device and the physics principles behind it.

Application

- ✓ Use equipment and materials safely and effectively to construct and modify the device.
- ✓ Demonstrate how the physics principles related to waves and/or sound can be applied to the device.

UNIT 4 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. Which of the following statements is true of waves passing through media? (8.1) K/U
   (a) Energy is transferred and lost as a wave passes through a material.
   (b) Sound waves travel faster in air than in water.
   (c) The speed of sound waves through a gas is affected by the temperature of the gas.
   (d) Waves travelling through a less rigid material travel faster and farther than through a rigid material.
2. Which three wave characteristics depend on one another? (8.3) K/U
   (a) amplitude, speed, phase
   (b) speed, wavelength, frequency
   (c) amplitude, direction, frequency
   (d) amplitude, waveform, speed
3. A vuvuzela supports a wave with a frequency of 235 Hz. If the wave travels at 335 m/s, what is its wavelength? (8.4) K/U
   (a) 0.7 m
   (b) 1.4 m
   (c) 14 cm
   (d) 100 m
4. If you know the linear density of a violin string, and want to calculate the speed of a wave on the violin string, which additional information is needed? (8.4) K/U
   (a) tension on the string
   (b) temperature of the string
   (c) time to complete a cycle
   (d) density of the violin's sounding board
5. A hypersonic test glider achieved a speed of Mach 20 before crashing. This means that the glider travelled
   (a) at 20 times the speed of sound
   (b) at 20 m/s
   (c) at 2 times the speed of sound
   (d) at $\frac{1}{20}$ the speed of sound (8.5) K/U
6. When two waves meet, one with amplitude 4 cm and the other with amplitude 2 cm, what are the possible maximum and minimum amplitudes of the resulting wave? (9.1) K/U
   (a) maximum 6 cm, minimum 2 cm
   (b) maximum 4 cm, minimum 2 cm
   (c) maximum 8 cm, minimum 0.5 cm
   (d) maximum 6 cm, minimum 6 cm
7. A didgeridoo (Australian indigenous wind instrument) produces a fundamental frequency of 60 Hz. How long is the didgeridoo? (Use 343 m/s as the speed of sound.) (9.2) T/I
   (a) 70 cm
   (b) 5.72 m
   (c) 1.59 cm
   (d) 1.43 m
8. Which of the following statements is true of amplitude? (9.4) T/I
   (a) When the difference between the frequency of a wave and its natural frequency increases, the amplitude of a wave increases.
   (b) A decrease in wave energy decreases a wave's amplitude.
   (c) When damping is increased, the amplitude of a wave increases.
   (d) When a system vibrates close to a harmonic, resonance occurs and the amplitude of the observed vibration decreases.
9. A truck is travelling at 30 m/s toward a stationary observer. If the truck sounds its horn at a frequency of 700 Hz, what frequency does the observer detect? (Use 340 m/s as the speed of sound.) (9.5) T/I
   (a) 638 Hz
   (b) 643 Hz
   (c) 762 Hz
   (d) 767 Hz
10. Which of the following statements correctly describes an aspect of hearing? (10.1) K/U
    (a) Vibrations of the pinna cause hairs to vibrate, thus determining the loudness of a sound.
    (b) The outer ear funnels sound into the cochlea.
    (c) When a sound wave enters the auditory canal, the eardrum vibrates at twice the frequency of the sound wave.
    (d) In the cochlea, vibrations are transformed into electrical impulses, which are then sent to the brain.
11. A 33 cm long violin string vibrates with a fundamental frequency of 196 Hz. If the violinist presses against the fingerboard 4 cm from the end of the string, what is the new fundamental frequency? (10.2) T/I
    (a) 172 Hz
    (b) 192 Hz
    (c) 196 Hz
    (d) 223 Hz

12. Which of the following is the wavelength of the third harmonic of a 33 cm long violin string? (10.2) T/I
    (a) 11 cm
    (b) 16.5 cm
    (c) 22 cm
    (d) 33 cm
13. Which of the following statements is true? (10.5) K/U
    (a) Sound waves produced by a function generator travel through Earth and reflect off the various layers.
    (b) S-waves can move through both solid and liquid material.
    (c) Earthquakes cause different types of waves that move through Earth and across the surface.
    (d) Geophysical exploration using seismic waves has never provided scientists with useful information about Earth's interior.
14. A bat sent out a pulse with a frequency of 80 kHz and a wavelength of 0.4 cm to locate its prey. If the bat received an echo after 0.2 s, how far away was the prey? (10.7) T/I
    (a) 16 m
    (b) 32 m
    (c) 64 m
    (d) 320 m

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

15. The "wave" at a sports stadium models a transverse wave. (8.2) K/U
16. Sound waves are created in air through a series of alternating compressions and rarefactions. (8.2) K/U
17. The amplitude of a wave is the distance between a wave's crest and trough. (8.3) K/U
18. The distance between the peaks of two adjacent waves is an example of wavelength. (8.3) K/U
19. Identical waves with a phase shift of 0.5 would match up crest to trough and trough to crest. (8.3) K/U
20. If you halve the frequency of a wave, you double the speed. (8.4) K/U
21. To prevent hearing damage, exposure to a sound level of 100 dB should be less than 15 min. (8.5) K/U
22. The frequency of audible sound waves ranges from 20 Hz to 20 000 Hz. (8.5) K/U
23. As the distance a sound travels increases, the energy of the wave decreases. (8.5) K/U
24. Noise pollution from a variety of sources can lead to damaged hearing. (8.7) K/U
25. If two similar waves are perfectly out of phase when they meet, constructive interference occurs and the sum of the amplitudes is doubled. (9.1) K/U
26. A standing wave occurs when the reflected wave interferes with the incident wave. (9.2) K/U
27. Free-end reflections result in waves with the opposite orientation to the original. (9.2) K/U
28. When a wave crosses between two different media, the wave will break into two waves, one of which will be partly transmitted and the other partly reflected. (9.2) K/U
29. When two waves with nearly identical frequencies interfere, the resultant interference pattern produces a rhythmic beat. (9.3) K/U
30. Engineers must design structures so that winds do not produce resonance resulting in wide vibrations. (9.4) K/U
31. As a moving sound source approaches a stationary observer, the observed frequency increases and the speed of the sound source is taken to be positive. (9.5) K/U
32. A strong current moving in the direction opposite to the direction of strong winds and waves can cause waves to combine to form a tsunami. (9.6) K/U
33. Typical hearing aids amplify sound and then send the sound into the auditory canal. (10.1) K/U
34. Music is characterized by waves of variable frequencies and amplitudes. (10.2) K/U
35. Sound quality in a concert hall is maximized when reverberation time is no more than a second or two. (10.3) K/U
36. Aeroelastic flutter can cause objects to vibrate at high frequencies. (10.4) K/U
37. Sympathetic vibration occurs when an object is vibrating and the input energy is greater than the energy lost to damping. (10.4) K/U
38. Aeroelastic flutter in an aircraft seems to arise from the aircraft itself rather than from air turbulence. (10.6) K/U
39. Elephants hear ultrasonic sounds with their trunk, feet, and ears. (10.7) K/U

To do an online self-quiz,
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UNIT 4 REVIEW

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

Knowledge

For each question, select the best answer from the four alternatives.

1. Which statement is false, as suggested by the universal wave equation, $v = f\lambda$? (8.4) K/U
   (a) If the frequency is held constant, the speed increases as the wavelength increases.
   (b) Speed is the product of the frequency and the wavelength.
   (c) If the wavelength is held constant, the speed increases as the frequency decreases.
   (d) If the speed is held constant, wavelength increases as the frequency decreases.
2. Which best describes sound waves? (8.2) K/U
   (a) transfer of energy from one place to another
   (b) transfer of mass from one place to another
   (c) positive displacement of particles
   (d) movement in a direction perpendicular to the direction of the wave

Use Figure 1 to answer Questions 3 to 5.

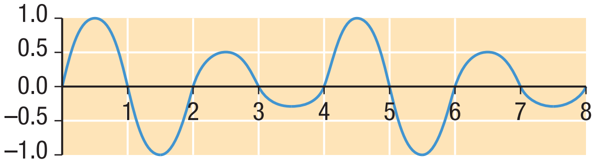


Figure 1

3. What is the amplitude of the wave? (8.3) K/U
   (a) 0.5 units
   (b) 0.75 units
   (c) 1 unit
   (d) 2 units
4. What is the wavelength of the wave? (8.3) K/U
   (a) 8 units
   (b) 4 units
   (c) 2 units
   (d) 1 unit
5. If the wave is moving 4 units to the right per second, what is its frequency? (8.4) K/U
   (a) 1 cycle per second
   (b) 1/2 cycle per second
   (c) 2 cycles per second
   (d) 8 cycles per second
6. If the frequency of a wave is 300 Hz and the wavelength is 1.5 m, what is the speed of the wave? (8.3, 8.4) K/U
   (a) 0.005 m/s
   (b) 200 m/s
   (c) 300 m/s
   (d) 450 m/s
7. If the frequency of a wave is 300 Hz and the wavelength is 1.5 m, how long does it take for a single wave to pass by? (8.4) K/U
   (a) 0.0033 s
   (b) 0.033 s
   (c) 200 s
   (d) 300 s
8. Balboa Park in San Diego, California, has an outdoor organ. When the air temperature increases, the fundamental frequency of one of the organ pipes
   (a) increases
   (b) decreases
   (c) stays the same
   (d) impossible to determine (8.4, 10.2) K/U
9. Which equation correctly states the relationship between the speed of a wave on a string and the linear density and tension of the string? (8.4) K/U
   (a) $v = \sqrt{\dfrac{F_T}{\mu}}$
   (b) $v = \sqrt{\dfrac{\mu}{F_T}}$
   (c) $v = \dfrac{\sqrt{F_T}}{\mu}$
   (d) $\mu = \dfrac{\sqrt{F_T}}{v}$
10. Which of the following actions will increase the speed of sound in air? (8.5) K/U
    (a) decreasing the air temperature
    (b) increasing the frequency of the sound
    (c) increasing the air temperature
    (d) increasing the amplitude of the sound wave

11. Which diagram in **Figure 2** shows a standing wave in a free-end system, such as in a brass instrument? (9.2) K/U

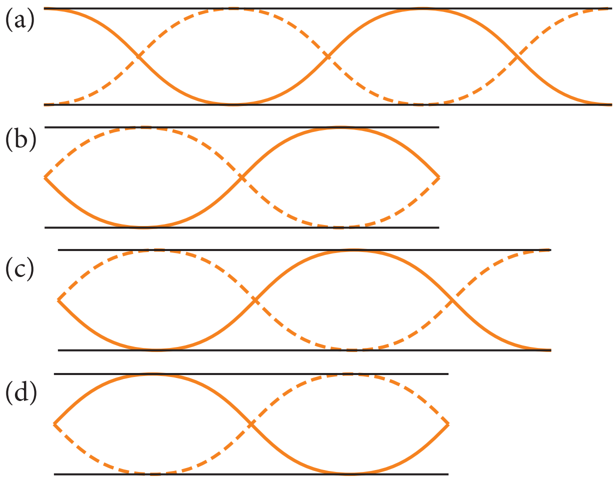


Figure 2

12. Which diagram in **Figure 3** shows the second harmonic for a violin string? (10.2) K/U

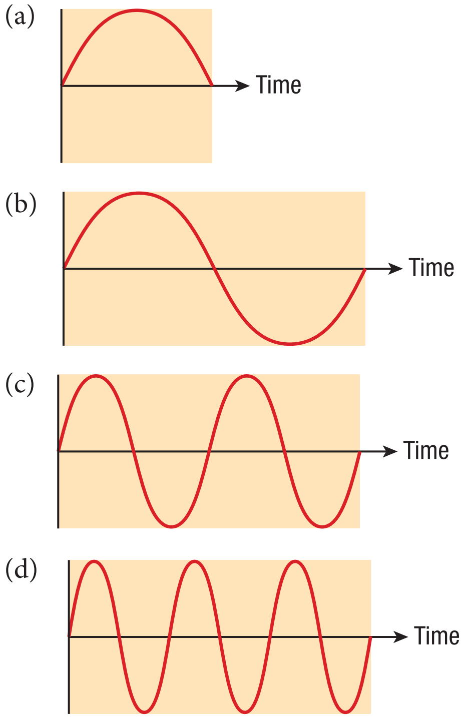


Figure 3

13. For the speed of sound to be 345 m/s, what must the air temperature be? (8.5) K/U
    (a) 8.1 °C
    (b) 18.1 °C
    (c) 19.3 °C
    (d) 22.4 °C

14. Which of the following definitions describes sound intensity? (8.5) K/U
    (a) loudness per metre
    (b) energy flowing through units of area
    (c) threshold of hearing between 1×10^{-12} W/m^2 and 1 W/m^2
    (d) decibels per cubic metre of volume

15. Of the following sounds, which is most likely to have an intensity level of 60 dB? (8.5) K/U
    (a) a rock concert
    (b) the turning of a page in this text
    (c) a cheering crowd at a football game
    (d) an alarm clock

16. Suppose you are on a hot-air balloon ride, carrying a buzzer that emits a sound of frequency f. If you accidentally drop the buzzer over the side while the balloon is rising at constant speed, what can you conclude about the sound you hear as the buzzer falls toward the ground? (8.5, 10.5) K/U
    (a) The frequency and intensity increase.
    (b) The frequency decreases and the intensity increases.
    (c) The frequency decreases and the intensity decreases.
    (d) The frequency remains the same, but the intensity decreases.

17. A pipe open at both ends resonates at a fundamental frequency, f_{open}. When one end is covered and the pipe is again made to resonate, the fundamental frequency is f_{closed}. Which of the following expressions describes how these two resonant frequencies compare? (9.2, 10.2) K/U
    (a) $f_{\text{closed}} = f_{\text{open}}$
    (b) $f_{\text{closed}} = \frac{3}{2}f_{\text{open}}$
    (c) $f_{\text{closed}} = 2f_{\text{open}}$
    (d) $f_{\text{closed}} = \frac{1}{2}f_{\text{open}}$

18. Which statement about the nodes of a standing wave on a string with two fixed ends is false? (9.2) K/U
    (a) The fixed ends are always nodes.
    (b) Adjacent nodes are separated by one wavelength.
    (c) Adjacent nodes are separated by a half wavelength.
    (d) The fundamental frequency occurs when the distance between adjacent nodes is from the standing wave pattern with the longest wavelength.

19. Which of the following frequencies is a higher harmonic of a string with a fundamental frequency of 150 Hz? (9.2) K/U
   (a) 200 Hz
   (b) 300 Hz
   (c) 400 Hz
   (d) 500 Hz
20. Which phrase best describes damping of a wave? (9.4) K/U
   (a) decreased velocity
   (b) constructive interference
   (c) decreased frequency
   (d) decreased amplitude
21. Which statement is appropriate for **Figure 4**? (9.5) K/U

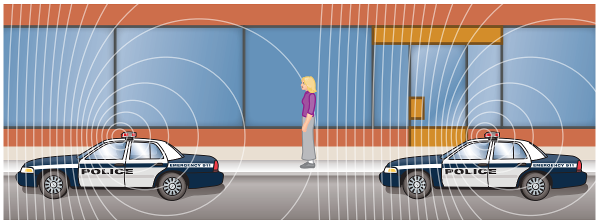


Figure 4

   (a) As the siren approaches the stationary observer, there are fewer sound waves per second, and the siren's frequency increases.
   (b) As the siren approaches the stationary observer, there are more sound waves per second, and the siren's frequency increases.
   (c) As the siren recedes from the stationary observer, there are more sound waves per second, and the siren's frequency decreases.
   (d) As the siren recedes from the stationary observer, there are fewer sound waves per second, and the siren's frequency increases.
22. Which statement describes a musical instrument with an air column that is open at both ends? (10.2) K/U
   (a) Antinodes are at both ends of the column.
   (b) The fundamental frequency occurs with the highest frequency and longest wavelength.
   (c) The fundamental frequency occurs when the length of the instrument equals the wavelength.
   (d) Nodes are at both ends of the column.
23. Which of the following is least likely to cause vibration in an aircraft? (10.6) K/U
   (a) engine operation
   (b) applying aerodynamic brakes
   (c) energy added to airflow around the wings is greater than energy lost
   (d) mass distribution

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

24. Sound travels fastest in a vacuum. (8.1) K/U
25. As an airplane flying with constant speed moves from a cold air mass into a warm air mass, the Mach number increases. (8.5, 8.6) K/U
26. Exposure to loud sounds, even for a short period of time, can cause hearing loss. (8.7) K/U
27. When two waves meet, the resultant wave's amplitude is the average of the two waves' amplitudes. (9.1) K/U
28. When a wave travels between two media and does not change its speed very much, more of the wave is transmitted than reflected. (9.2) K/U
29. The beat frequency is the difference between the frequencies of the waves interfering to produce a beat. (9.3) K/U
30. Standing waves are an example of resonance. (9.4) K/U
31. Rogue waves are caused by earthquakes. (9.6) K/U
32. The brain uses the number and location of hairs in the inner ear to determine the loudness and frequency of a sound. (10.1) K/U
33. Good concert hall acoustical design allows only direct sound to reach the audience. (10.3) K/U
34. Resonance caused the Tacoma Narrows Bridge to fall. (10.4) K/U
35. Body waves travel through Earth's atmosphere. (10.5) K/U
36. Dolphins can detect small objects over great distances using echolocation. (10.7) K/U

Match each term on the left with the most appropriate description on the right.

37.

(a)	first harmonic	(i)	λ
(b)	second overtone	(ii)	$\frac{3\lambda}{2}$
(c)	second harmonic	(iii)	$\frac{5\lambda}{2}$
(d)	fourth harmonic	(iv)	loop
(e)	fourth overtone	(v)	2λ
(f)	destructive interference	(vi)	medical imaging
(g)	seismic waves	(vii)	bats' hunting
(h)	acoustical beat	(viii)	Earth exploration
(i)	echolocation	(ix)	piano tuning
(j)	ultrasonic waves	(x)	noise-cancelling earphones (8.5, 9.1, 9.2, 9.3, 10.5, 10.7) K/U

Write a short answer to each question.

38. A sound wave travels with a speed of 334 m/s through air with a frequency of 172 Hz. How far apart are the wave crests? (8.3) K/U
39. Humans hear sound with frequencies as low as 20 Hz. What is the wavelength of such a sound? (8.3) K/U
40. Explain or show the relationship between two waves with a phase shift of $\frac{1}{4}\lambda$. (8.3) K/U

Use Figure 5 to answer Questions 41 to 44.

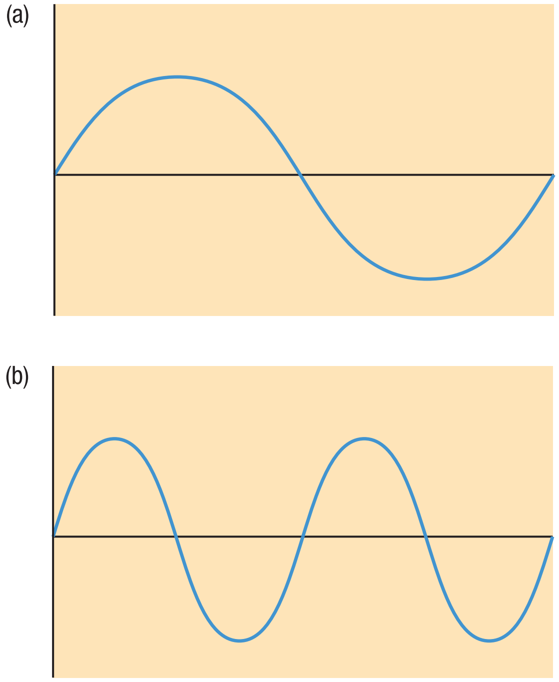


Figure 5

41. How do the frequencies of the two waves compare? (8.3) K/U
42. How do the wavelengths of the two waves compare? (8.3) K/U
43. How do the amplitudes of the two waves compare? (8.3) K/U
44. Identify where the two waves share a node. (9.2) K/U
45. What is the linear density of 6 m of rope with a mass of 330 g? (8.4) K/U
46. A man standing on a dock is watching the waves pass by the end of the dock. He times the passage of the waves as one crest every 2.5 s. He estimates the distance between two crests to be 2.0 m. How fast are the waves moving? (8.4) K/U
47. A tour guide shouts across a canyon. At a temperature of 20 °C, her echo is heard 2.00 s later. How wide is the canyon? (8.5) K/U T/I
48. What does it mean to say that a conversation in a room is at Mach 1? (8.5) K/U
49. Determine the fundamental frequency of a vibrating string if two successive harmonics of the string are 180 Hz and 270 Hz. (9.2) K/U
50. Explain what type of reflection is created by flicking a fishing rod. What is the orientation of the reflected wave? (9.2) K/U
51. The distance between successive antinodes in a standing wave pattern is equivalent to how many wavelengths? (9.2) K/U
52. A standing wave is produced in a rope by vibrating one end with a frequency of 75 Hz. The distance between the first and fourth nodes is 45 cm. How long is the wavelength? (9.2) K/U
53. Describe the Doppler effect when a moving ambulance with its siren on approaches an observer standing on a street corner. (9.5) K/U
54. Create a Venn diagram comparing rogue waves and tsunamis. (9.6, 10.5) K/U C
55. For each numbered step in **Figure 6**, write one sentence that explains the different stages of how we hear. (10.1) K/U C

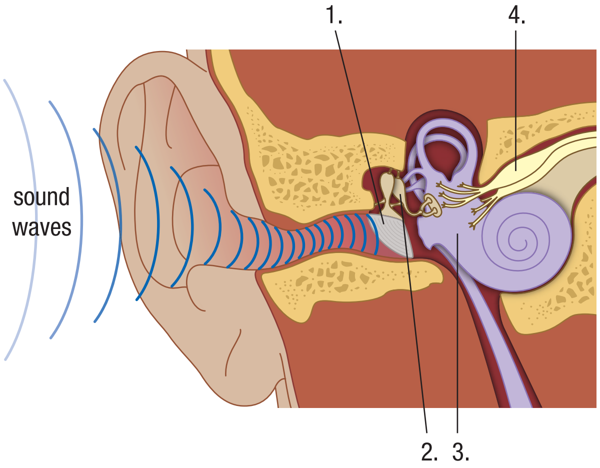


Figure 6

56. The auditory canal has a natural frequency of about 3500 Hz. If the speed of sound waves inside the canal is about 350 m/s, what is the length of the auditory canal? (10.1) K/U
57. Why does a vibrating guitar string sound louder when placed on the instrument than it would if allowed to vibrate in the air while off the instrument? (10.2) K/U
58. What happens to the pitch of a musical note if the frequency of the note is decreased? (10.2) K/U
59. How can the frequency produced by a kettledrum be changed? (10.2) K/U

60. At what frequencies do the higher harmonics of an open-air-column musical instrument occur? (10.2) K/U

61. A concert choir has a loudness of 73 dB. What will the sound level drop to after the reverberation time? (10.3) K/U

62. What can be done to shorten the reverberation time in a concert hall? (10.3) K/U

63. Explain how a mass damper improves a building's structural safety. (10.4) K/U

64. The length of a closed-end air column is how many wavelengths of the first harmonic? (10.2) K/U

Understanding

65. Explain why no work is done when a wave passes through a medium. (8.1) K/U

66. Explain why sound waves can be described as pressure waves. (8.2) K/U

67. In your own words, describe and distinguish between wave speed, wavelength, and wave frequency. (8.3) K/U

68. A violin string with a mass of 0.35 g is 33 cm long. The frequency of a wave supported by the string is 196 Hz. (8.4) T/I
    (a) What is the speed of the wave?
    (b) What is the linear density of the string?
    (c) What is the tension on the string?

69. Different factors determine the pitch created by a string fixed at each end. Copy **Table 1** into your notebook. For each factor listed, identify the effect that each factor will have on the pitch you would hear if the factor is increased or decreased. (8.4, 10.2) K/U

Table 1 Pitch Variation

Variable	Increased	Decreased
tension		
length		
diameter		
density		

70. Explain how constructive and destructive interference can be demonstrated when sending pulses from each end of a Slinky. (9.1) K/U

71. (a) How does a free-end reflection help explain the change in a wave's behaviour at a media boundary at which it slows down?
    (b) How does a fixed-end reflection help explain the change in a wave's behaviour at a media boundary at which it speeds up? (9.2) K/U

72. Explain how standing waves are examples of resonance. (9.4) K/U

73. Why does a cochlear implant work better than a hearing aid for a person with serious hearing loss? (10.1) K/U

74. Explain or demonstrate how noise and music are different. (10.2) K/U

75. Two different auditorium designs are shown in **Figure 7**. The arrows show sound coming from the stage and give a general idea of how the sound will reflect toward the audience. (10.3) K/U C
    (a) Which design has better acoustics? Explain your reasoning.
    (b) For the auditorium with inferior acoustics, describe the most obvious major design flaw.

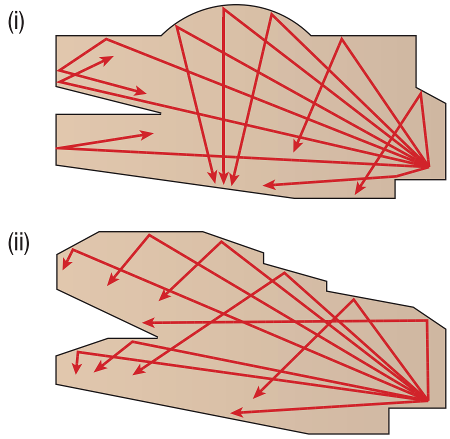


Figure 7

76. A parent pushes a child on a swing, and the swing develops large amplitudes.
    (a) Describe why this happens.
    (b) Will the swing develop large amplitudes no matter how much the parent pushes? (10.4) K/U

77. How are seismic waves used to gather information about Earth's interior? (10.5) K/U

Analysis and Application

78. A lightning flash dissipates an enormous amount of energy and is essentially instantaneous. How is the energy transformed into the sound waves of thunder? (8.1) T/I

79. To double the speed of a wave, by what factor would you change (a) the tension or (b) the linear density on a string? Explain your answer mathematically. (8.4) K/U

80. An autofocus camera used indoors sends out a pulse of sound and measures the time taken for the pulse to reach an object, reflect off it, and return to be detected to set the focus. If the camera is taken outdoors, where the temperature is cold, can the temperature affect the camera's focus? Explain your answer. (8.5) K/U T/I A

81. Intensity is said to be an objective measure of sound while loudness is said to be subjective. Explain why one term is objective and the other is subjective. (8.5) T/I

82. Use **Table 2** to answer the following questions. (8.5) T/I

Table 2 Typical Sound Levels

Type of sound	Sound level (dB)	Sound intensity (W/m^2)
normal breathing	10	1×10^{-11}
whisper	20	1×10^{-11}
power saw	120	1
rain	130	10
military jet taking off	140	100

(a) Give an example of two sounds from the table, one that is twice as loud as the other.

(b) By what factor do the intensities of the two sounds from (a) compare?

83. Explain how the distance to a lightning bolt can be determined by counting the seconds between the flash and the sound of thunder. (8.5) K/U A

84. How might an acoustic shadow affect the interpretation of an ultrasound medical test? (8.5, 10.3) K/U

85. Are longitudinal waves in air always audible as sound, regardless of frequency or intensity? Explain your answer. (8.5, 10.1) T/I

86. Dolphins produce sounds ranging from 1.5 kHz to 11.0 kHz and can hear sounds up to 150 kHz. The high-frequency "clicks" of the bottle-nosed dolphin include sounds below 20 kHz and up to 120 kHz. How do these ranges compare to the range of human hearing? (8.5, 10.1, 10.7) T/I

87. The land vehicle Thrust SSC achieved a land speed of 1228 km/h in 1997 at an elevation of 1191 m. Determine if this car broke the sound barrier, and explain how the achievement would be different if the car were driven at sea level. (8.6) K/U T/I

88. Contrast the creation of the first harmonic frequencies for (a) a tube with open ends and (b) a tube with one open end and one closed end. (9.2) K/U

89. Based on what you have learned about open and closed air columns, explain the purpose of air holes on a clarinet. (9.2) K/U

90. A pipe resonates at successive frequencies of 540 Hz, 450 Hz, and 350 Hz. Is this an open or a closed pipe? (9.2) T/I

91. Explain why the bass notes of a car radio are heard by people on the street and not the high notes. (9.2) T/I

92. Beats can easily be heard on a guitar. When a finger is placed at the fifth fret of the second string, the note produced when the string is plucked should be identical to the note from the first string when it is plucked. When you pluck both strings together, and one of the strings is slightly out of tune, you will hear a very pronounced beat frequency. What happens to the beat frequency as the string tension is changed in small increments from too low for the intended tuning to too high? (9.3) T/I

93. Despite a reasonably steady hand, a person often spills his coffee when carrying it. Discuss resonance as a possible cause of this difficulty, and devise a means for solving the problem. (9.4) K/U

94. You see a video on the Internet of a crystal glass being shattered as an opera singer hits a certain note. Explain why this might occur. (9.4) T/I

95. Explain what happens to the detected frequency for a jet flying near the speed of sound as it passes a stationary observer below. (9.5, 9.6) K/U

96. Suppose you snip off the corners of one end of a paper straw so that the end tapers to a point, as shown in **Figure 8**. Then you flatten it, for example, by chewing on the tapered end. Suppose you put your lips around the tapered end of the straw, press them together slightly, and blow through the straw. You hear a steady tone, then you slowly snip off a piece of the straw at the other end. (10.2) T/I

(a) How does the frequency of the sound change as the straw becomes shorter?

(b) Why does this change occur?

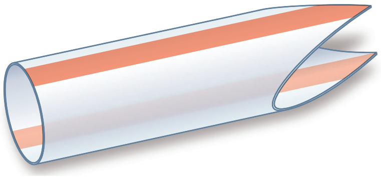


Figure 8

97. Explain the audible tone produced by drawing a wet finger around the rim of a crystal glass. (10.2) T/I

98. A musical octave is separated into 12 equal divisions called semi-tones, each differing from the next by a factor of $2^{n/12}$. **Table 3** shows the semi-tones and their frequencies beginning with A, which has a frequency of 440 Hz. Use Table 3 to answer the following questions. (10.2) T/I C

Table 3 Musical Frequencies

Note	*f* (Hz)	Note	*f* (Hz)	Note	*f* (Hz)	Note	*f* (Hz)
A	440	C	523	D$^{\#}$	622	F$^{\#}$	740
A$^{\#}$	466	C$^{\#}$	554	E	659	G	784
B	494	D	587	F	698	G$^{\#}$	831

(a) Explain or show why the frequency of a note 12 semi-tones above A is 880 Hz.
(b) What is the ratio of the frequency of E to that of A?
(c) If an open tube of length L has a fundamental frequency of 440 Hz, what length of tube would produce an E?

99. A piezoelectric material is a natural or manufactured substance that produces an electrical charge when subjected to a mechanical strain such as being hit or vibrated. If the material is subjected to an electrical current, it will bend or vibrate depending on the material and the nature of the current. How could the properties of piezoelectric materials be used to reduce vibrations and noise? (10.4, 10.6) T/I

100. A blowing whistle is attached to the roof of a car that moves around a circular race track. Assuming you are standing near the outside of the track, explain the nature of the sound you hear as the whistle comes by each time. (9.5) K/U C

Evaluation

101. Evaluate the following statement. Explain your reasoning. "The speed of sound is the same for all wavelengths." (8.4) T/I

102. **Figure 9** shows an object moving very quickly to the right. (8.6, 9.5) T/I
(a) Relate Figure 9 to the speed of sound and the sound barrier.
(b) Modify the diagram to show an object moving at a speed that is (i) less than the speed of sound and (ii) greater than the speed of sound. Support your reasoning for each diagram using the Doppler effect and/or the speed of sound in air.

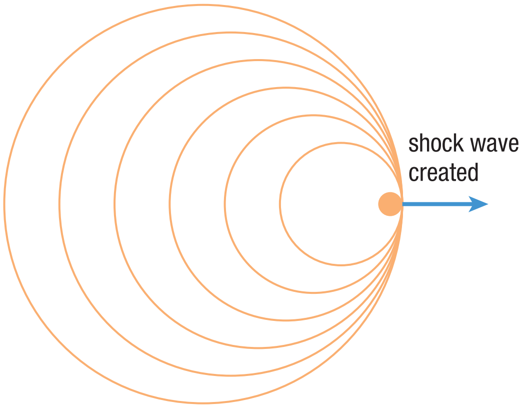


Figure 9

103. A friend suggests all people can reduce the effect of noise pollution at work by using earplugs all day. Evaluate the effectiveness of this solution. (8.7) T/I

104. When is resonance to be avoided, and when is it desirable? (9.4, 10.4) T/I

105. Decide if a dome-roofed stadium or a parabola-shaped shell would be suitable for a concert venue. (10.3) T/I

106. Compare and contrast mechanical resonance and aeroelastic flutter. (10.4) T/I

Reflect on Your Learning

107. How did your learning in this unit connect to your prior knowledge of waves? T/I

108. Explain an idea that you initially had difficulty with but gained an understanding of in this unit. T/I

109. What was the most surprising thing you learned in this unit? C

110. How did the information you learned in this unit affect your thinking about the dangers and benefits of vibrations and waves? T/I

111. What further aspects of waves and sound and their applications would you like to know more about? T/I

Research

GO TO NELSON SCIENCE

112. Research the 1929 Grand Banks earthquake and tsunami. Prepare a visual presentation. Provide observations of eyewitness or newspaper accounts contemporary with the actual events. Contrast these reports with more recent scientific explanations in terms of seismic wave activity and landslides. T/I C

113. Investigate the criteria for acceptable levels of noise at the federal and provincial levels. Consult information provided by the Canadian Centre of Occupational Health and Safety. Prepare a brief presentation explaining criteria levels and exchange rates. Include some sound samples. Discuss the implications of standards on particular types of occupational or recreational noise. T/I C

114. Investigate the mathematical relationship between sound intensity and loudness. Prepare a brief presentation explaining this relationship. Pose and solve some problems illustrating this relationship. T/I C

115. The Bay of Fundy is legendary for its high tides. Find out what tidal resonance means. Which body of water holds the world's record for the highest tides? Write a short report about your findings. T/I C

116. The Canadian composer R. Murray Schafer introduced the idea of sound ecology in his World Soundscape Project. Research his work on sounds in the environment and noise pollution. Listen to a recording of the Vancouver Soundscape. Prepare a brief podcast discussing the history of this project and the role it has played in promoting acoustic technology and sound legislation. T/I C

117. Ultrasound stethoscopes make use of the Doppler effect. As a result, these stethoscopes are more effective than traditional stethoscopes in noisy environments. Prepare a brief report on how ultrasound stethoscopes make use of the Doppler effect. T/I C

118. Sound therapy is said to have a healing effect on both the creator of the sound and the listener. Research sound therapy, and make a brief presentation on sound therapy with instruments such as the didgeridoo. Include audio clips if possible. T/I C

119. Find out and explain how research on bat echolocation has been applied to robotics. T/I C

120. Scales provide a palette of tones for melodies and harmonies to someone writing and playing music. The scales are based on relationships between the frequencies of successive tones. Prepare a brief presentation contrasting the frequencies and wavelengths of the notes in a musical major scale and its related minor scale. Compare and contrast the tones in these two scales. C

121. The production of human sounds depends on the regulation of airflow through the lungs, throat, nose, and mouth. This airflow is altered in various ways by systems involving the lungs, trachea, voice box, and oral and nasal cavities. Investigate the production and frequencies of men's and women's voices. Prepare a brief report on the physiology and physics of speech. T/I C

122. Investigate and prepare a brief report on the acoustical properties of a nearby auditorium or sports arena. Consider major elements of design as well as materials. You may wish to construct a scale model and explain how an acoustic model would differ from an architectural model. T/I C

123. Acoustical feedback occurs when sound coming out of a speaker travels back into the microphone and is re-amplified. Investigate a microphone and sound system or the microphone in a hearing aid for feedback. Prepare the text for a short email that you could send to a friend explaining how feedback can be suppressed. T/I C

124. You have been hired to design an open office that will minimize noise pollution for workers. The owners of the company do not want to insert walls in the space because they want to foster cooperation among the employees. However, they also want to minimize distractions due to noise from other workers. Research acoustics principles as applied to office design. In a simple diagram, design an office suited for eight employees. Include a half-page explanation describing how you have achieved your goals. Mention the different ways sound can reach the workers and how your design helps reduce the amount of sound. T/I C

125. Research how the Doppler effect has been applied to monitoring heart rates. Include in your research how this new method is an advantage over older methods. Describe any difficulties with using the Doppler effect to monitor heart rate, and explain how these difficulties have been overcome. T/I C

126. The blue whale (**Figure 10**) uses echolocation for reasons other than detecting prey. Research blue whales and echolocation. Prepare a blog or wiki page that explains two ways that blue whales use echolocation. Include an audio file of the blue whale's sound. K/U C A

Figure 10

UNIT 5

Electricity and Magnetism

OVERALL EXPECTATIONS

- analyze the social, economic, and environmental impact of electrical energy production and technologies related to electromagnetism, and propose ways to improve the sustainability of electrical energy production
- investigate, in qualitative and quantitative terms, magnetic fields and electric circuits, and solve related problems
- demonstrate an understanding of the properties of magnetic fields, the principles of current and electron flow, and the operation of selected technologies that use these properties and principles to produce and transmit electrical energy

BIG IDEAS

- Relationships between electricity and magnetism are predictable.
- Electricity and magnetism have many technological applications.
- Technological applications that involve electromagnetism and energy transformations can affect society and the environment in positive and negative ways.

UNIT TASK **PREVIEW**

In the Unit Task, you will build a working model of a power plant. You will provide a source of energy for the power plant and build all the parts. You will also investigate what factors improve efficiency. The Unit Task is described in detail on page 622. As you work through the unit, look for Unit Task Bookmarks to see how information in the section relates to the Unit Task.

WHAT IS THE LIFESPAN OF A CELLPHONE?

Cellphones are no longer used only to make calls. Many cellphones now include digital cameras, touch screens, keyboards, applications (such as calendars and calculators), and MP3 players. To make all this possible, experts in software, electronics, and manufacturing design the phone. Once designed, the cellphone is manufactured and then shipped across great distances to your local electronics store. The consumer who buys the cellphone will probably only use it for about 18 months (on average in North America). Then the consumer will likely buy another phone with new features.

What will you do with your old cellphone? You may consider not purchasing the latest model and keep your current cellphone for as long as it works. You may also take your phone to an “e-cycling” facility.

E-cycling is the process of recycling or reusing parts of electronic devices such as cellphones and computers. E-cycling is becoming more important as more people buy, use, and throw away electronic devices. We already recycle materials such as pop cans and newspapers, but we are now learning that electronic gadgets also need to be recycled. Some companies will take electronic devices that people no longer want, or that no longer work. The devices are taken apart and the parts that are salvageable are sold back to the manufacturers. Some devices can even be refurbished and sold at a much reduced cost.

E-cycling reduces the amount of waste and chemicals entering the environment from old and broken electronics. However, e-cycling has some costs associated with it, such as for operating the e-cycling facility and recovering useful parts. Some of these costs are passed on to the consumer.

Questions

1. What materials or parts do you think are required to manufacture a cellphone?
2. How many cellphones have your friends or family owned? What did they do with the old ones?
3. When you purchase an electronic device, your bill includes a surcharge to help pay for e-cycling the device. How do you feel about this surcharge?
4. Some of the chemicals in cellphones are arsenic, mercury, cadmium, lead, and brominated flame retardants. These materials are all toxic to humans and wildlife. What might you consider doing to prevent these chemicals from ending up in our landfills and waterways?
5. What responsibilities to the environment should manufacturers of cellphones have when designing cellphones?

UNIT 5 ARE YOU READY?

CONCEPTS

- energy transformations
- electrical energy
- electric current
- electric potential difference
- electrical resistance
- series and parallel circuits
- methods of electricity generation
- renewable and non-renewable sources
- Ohm's law
- properties of magnets

SKILLS

- connecting series and parallel circuits
- identifying the parts of a circuit
- drawing series and parallel circuits using appropriate circuit symbols
- recognizing resistances on a graph of voltage versus current
- solving problems using three-variable equations

Concepts Review

1. Describe an energy transformation that can be used to produce electrical energy. K/U C
2. Why is electrical energy useful? Give at least one example. K/U
3. (a) What is electric current?
   (b) In a conducting wire, which charged particles are involved in electric current?
   (c) Identify the two different types of current electricity. K/U C
4. (a) Give an example of something that has an electric potential difference.
   (b) State a typical value of the electric potential difference for the example you chose. K/U
5. Describe what is meant by electrical resistance. K/U
6. Give an example of something that has a high resistance and something that has a low resistance. Explain your choices. K/U
7. Does a conductor have high resistance or low resistance? Explain. K/U
8. (a) Draw a series circuit containing one battery, and your choice of loads and switches.
   (b) Draw a parallel circuit containing one battery, and your choice of loads and switches. K/U C
9. Circuit A has all of the parts connected in one path, while circuit B has all of the parts connected along several paths. Which circuit best fits the description of a series circuit? K/U C
10. Identify as many renewable and non-renewable sources of energy as you can. K/U
11. (a) List conventional and alternative methods of electricity generation. Some examples are shown in **Figure 1**.
    (b) Choose one method from each list in (a). Identify a benefit and a disadvantage to the environment for each method. K/U A

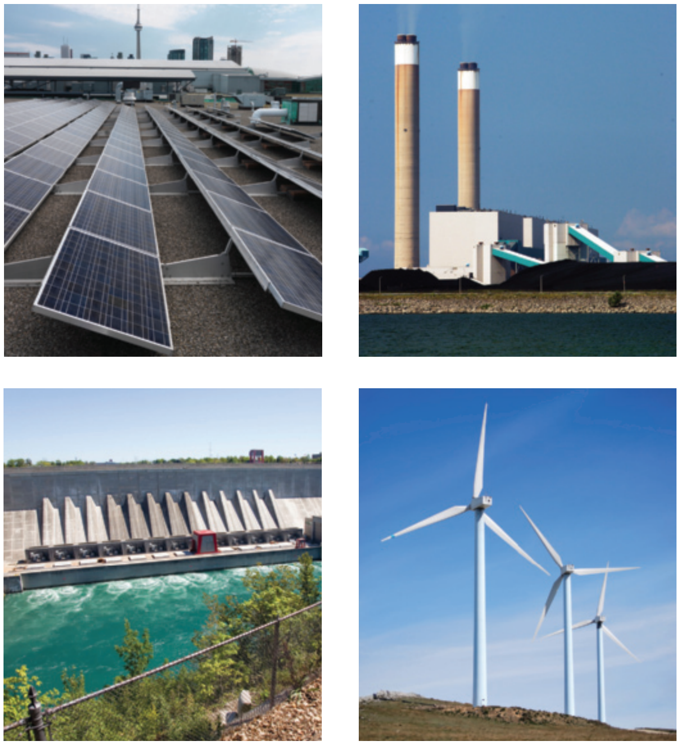
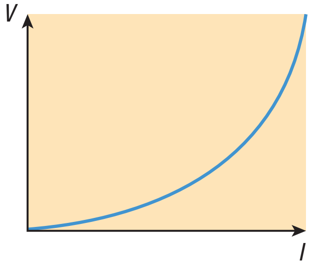
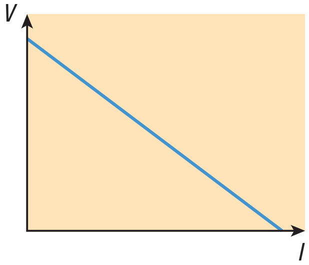
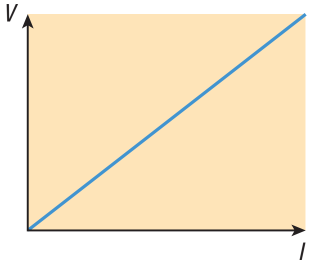


Figure 1 Some methods of electricity generation

12. Which of the following graphs best describes an electrical device that obeys Ohm's law? K/U

(a)


(c)


(b)


13. What happens when the north poles of two magnets are brought near one another (**Figure 2**)? K/U

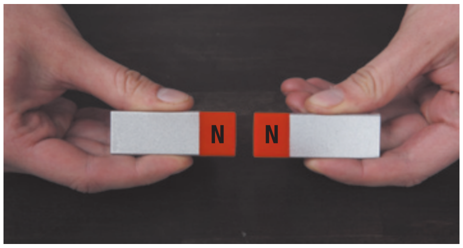
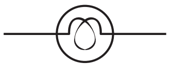


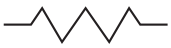
Figure 2

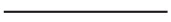
Skills Review

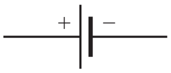
14. (a) A group of students connect a lead from a DC power supply to a switch. They use another lead to connect the switch to one terminal on a motor. They connect the other terminal of the motor back to the DC power supply with another lead. Have they created a series circuit or a parallel circuit?
    (b) For the circuit in part (a), identify the source of electrical energy, the load, the conducting wires, and the control device. K/U T/I

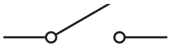
15. Identify the following circuit symbols: K/U

(a)


(b)


(c)


(d)


(e)


16. (a) Draw a circuit that contains a battery connected in series with a motor followed by two lamps connected in parallel with each other. Include switches to control each lamp independently.
    (b) What would happen if both switches were closed?
    (c) What would happen if both switches were open?
    (d) What would happen if one switch was closed? K/U T/I C

17. (a) Using the data in **Table 1,** plot a graph of current versus electric potential difference for a resistor. Use a line of best fit.

Table 1

Current (A)	Electric potential difference (V)
0.017	2.0
0.033	4.0
0.050	6.0
0.066	8.0
0.083	10.0

    (b) Calculate the slope of the line of best fit to find the resistance. Include the units of the slope.
    (c) On the graph, sketch a line showing a resistance of less than 120 Ω. K/U T/I C

18. Ohm's law can be written as $R = \frac{V}{I}$. T/I
    (a) Rearrange the equation to solve for V.
    (b) Rearrange the equation to solve for I.
    (c) What factors does I depend on?

19. Solve for the variable in each equation. Express your answer to part (b) as an improper fraction and as a decimal number. T/I
    (a) $14 = 7 + X + 2$
    (b) $\frac{1}{X} = \frac{1}{7} + \frac{1}{3}$

CAREER PATHWAYS **PREVIEW**

Throughout this unit you will see Career Links in the margins. These links mention careers that are relevant to Electricity and Magnetism. On the Chapter Summary page at the end of each chapter you will find a Career Pathways feature that shows you the educational requirements of the careers. There are also some career-related questions for you to research.

CHAPTER

11 Electricity and Its Production

KEY CONCEPTS

After completing this chapter you will be able to

- describe the following electrical quantities: electrical energy, power, electric current, electric potential difference, and resistance
- compare the efficiency of different power production technologies
- understand the movement of charge through a circuit
- describe properties of electric potential difference and current for series, parallel, and mixed circuits
- explain resistance in circuits and be able to determine the equivalent resistance in series, parallel, and mixed circuits
- design, build, analyze, and solve problems in series, parallel, and mixed circuits

What Are the Properties of Electricity, and How Does Electricity Move Through a Circuit?

Electricity is one of the most important and essential forms of energy. In an emergency, ambulances, the 911 phone system, and hospital equipment all require electricity. We are also accustomed to the convenience of electricity; you can get a cold drink from the refrigerator, heat up pizza in the microwave oven, and sit down to watch television in an air-conditioned home.

In Ontario, electrical energy is produced using a variety of methods. Each method has its advantages and disadvantages. For example, the Ontario provincial government plans to build a new nuclear power plant to expand the current nuclear plant in Darlington. The new plant will be able to generate energy to meet Ontario's growing electricity needs, but the resulting radioactive waste must be carefully managed and stored for thousands of years. Alternative methods of generating electricity (for example, wind and solar energy) are relatively new and have not yet been widely adopted.

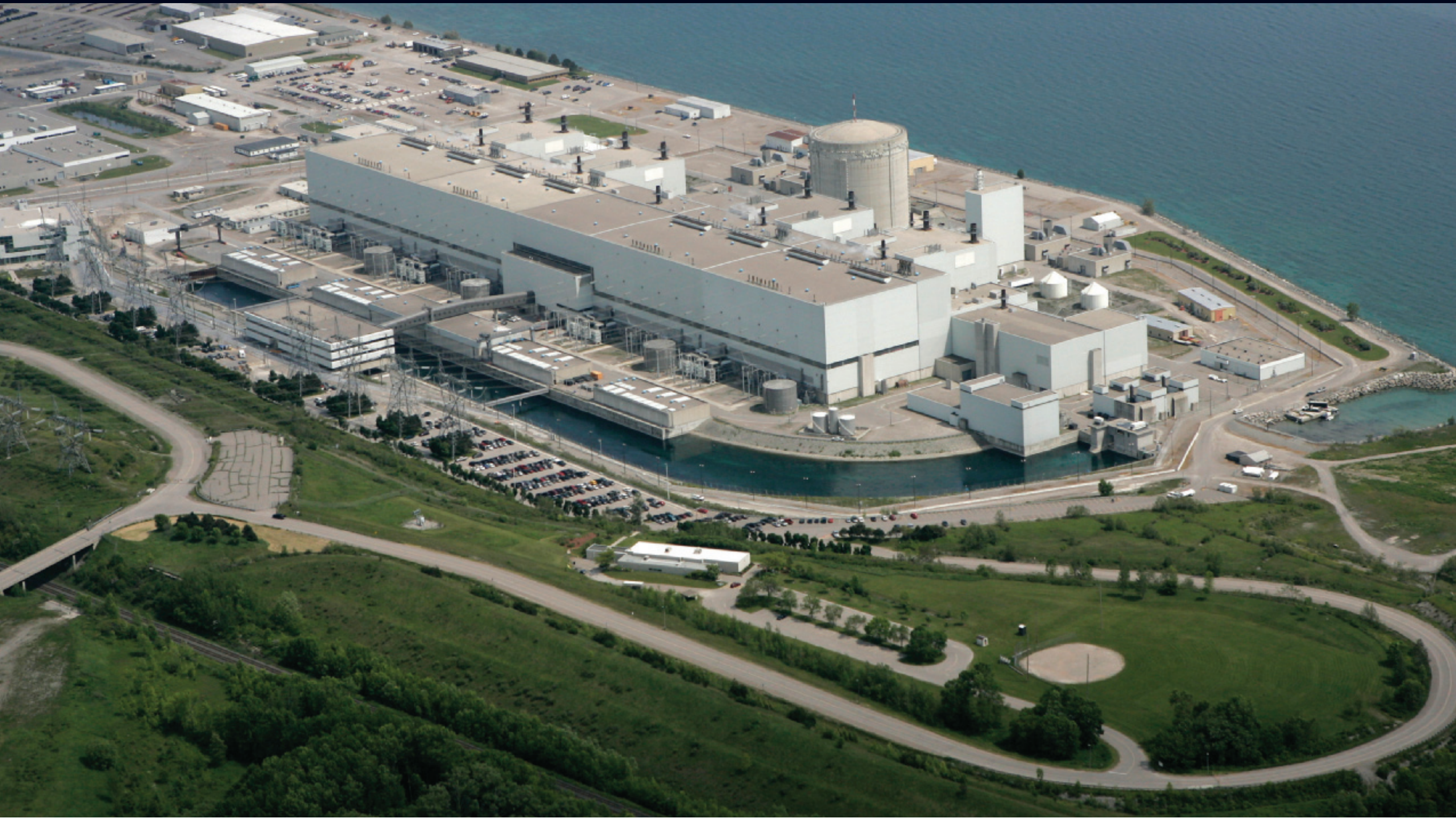
Once electricity is generated, it must be transferred from power plants to the places where it will be used. It travels through a giant circuit spread out through the entire province and beyond. During its transfer, the electricity must be controlled by measuring and keeping track of various properties, such as current and power. It is important to understand the properties of electrical circuits to prevent problems such as electricity outages. We want our electricity to be reliably produced, transferred, and available on demand. The challenge we face as consumers of electricity is to use energy wisely. Conserving energy means that we spend less money on electricity and also reduce the environmental impacts of generating electricity. The challenge faced at the power plants is to produce electricity efficiently while considering environmental effects such as pollution, habitat destruction, and climate change.

In this chapter, you will examine electricity and how it is produced. You will then learn about the properties that we need to understand to be able to produce, transfer, and use electricity efficiently. The properties of electricity can be quantified by measuring the electric potential difference, electric current, and electrical resistance.

STARTING **POINTS**

Answer the following questions using your current knowledge. You will have a chance to revisit these questions later, applying concepts and skills from the chapter.

1. Fossil fuel power plants are still the most common method of generating electricity. Why do you think this is the case?
2. Why is it dangerous to plug too many electrical devices into a single outlet?
3. What will happen to an electric current as it encounters a parallel circuit?



Mini Investigation

Building an LED Circuit

Skills: Performing, Observing, Analyzing

SKILLS HANDBOOK A2.1, A2.4

Light-emitting diodes (LEDs) are special kinds of devices that emit light. They have become very popular because they need very little energy to work. In this activity, you will build an LED circuit and observe the direction of the flow of electricity.

Equipment and Materials: 1 LED; 2 AA cells; 2 cell holders; approximately 6 alligator clip leads

1. Place the cells in their holders. Make a circuit using only one AA cell and the LED as shown in **Figure 1**. Connect the circuit and observe. Now reverse the connection of the LED by reversing the positions of the leads on the battery. Observe.
2. Now make a circuit using two AA cells by connecting the positive terminal of one cell to the negative terminal of the other cell. Connect the two cells with the LED. Observe. Now reverse the connection of the LED. Observe.

A. Did the LED light when you used just one cell? Did the way you connected the LED change the outcome? T/I

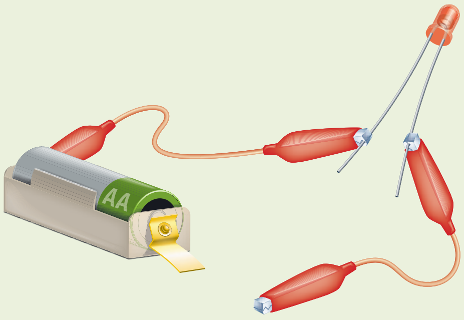


Figure 1

B. Did the LED light when you used two cells? Did the way you connected the LED change the outcome? T/I

C. Does electricity flow in a particular direction? Explain. Did part of the investigation support your answer? T/I

11.1 Electrical Energy and Power Plants

Imagine that you could not heat your home in the winter, cook food on a stove, or make a phone call in an emergency. Imagine not being able to use a computer, play video games, watch television, or keep food fresh in a refrigerator. We are very dependent on electricity.

What Is Electricity?

Electricity is something we generally take for granted. It is something we cannot see, hear, or touch. Electricity is also difficult to describe. In physics, the word "electricity" refers to electrical energy and the movement of charge. When we say, "the electricity went out" or "electricity is expensive," what we are really saying is, "electrical energy has stopped being transferred" or "generating electrical energy is expensive."

As you learned in Chapter 5, the law of conservation of energy states that no energy is lost when energy is transformed. This applies to the generation of electricity at power plants, where different types of energy are transformed into electrical energy. For example, in a hydroelectric power plant, kinetic energy from falling water is transformed into electrical energy (**Figure 1**). In a natural gas or nuclear power plant, thermal energy is transformed into electrical energy.

How does the electrical energy get from the power plant to where it is needed? Electricity is transferred through conducting wires in transmission lines. Then electrical devices in your home, at school, and at work transform the electrical energy into another form of energy to perform a task. For example, electrical energy is converted into kinetic energy in an electric fan, sound energy in a speaker system, and into thermal energy in an electric heater.

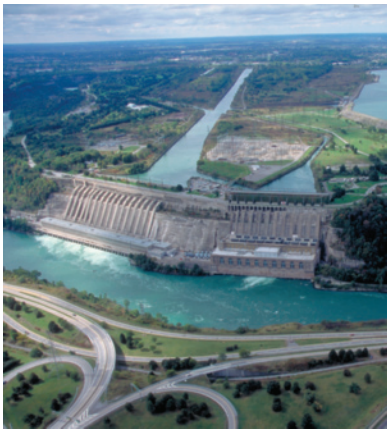


Figure 1 This hydroelectric power plant is transforming the kinetic energy of the falling water into electrical energy.

Electrical Power

electrical power (*P*) the rate of transformation of electrical energy

Recall from Chapter 5 that power (P) is the rate at which energy is transformed. **Electrical power** is the rate at which electrical energy is produced or consumed in a given time. In this chapter, we will use the terms "power" and "electrical power" interchangeably.

The equation that describes power is $P = \frac{\Delta E}{\Delta t}$. Power is expressed in watts (W), and electrical devices have power ratings that vary widely. In the following Tutorial, you will use the power equation to determine how much power is used by an electrical device.

Tutorial 1 Using the Power Equation

In the following Sample Problem, we will use the equation $P = \frac{\Delta E}{\Delta t}$ to determine how much power is used to charge a cellphone.

Sample Problem 1

Calculate the power required to charge a cellphone if 740 J of energy is transferred in 1.0 min.

Given: $\Delta E = 740\text{ J}$; $\Delta t = 1.0\text{ min}$

Required: P

Analysis: $P = \frac{\Delta E}{\Delta t}$

Solution: First convert time to seconds to get the answer in joules per second (J/s), or watts (W):

$$\Delta t = 1.0\ \cancel{\text{min}} \times \frac{60\text{ s}}{1\ \cancel{\text{min}}}$$

$$\Delta t = 60\text{ s}$$

$$P = \frac{\Delta E}{\Delta t}$$

$$= \frac{740\text{ J}}{60\text{ s}}$$

$$P = 12\text{ W}$$

Statement: The power required to charge the cellphone is 12 W.

Practice

1. What is the power rating of a digital camera that transforms 120 J in 25 s? T/I [ans: 4.8 W]
2. How much power does a hair dryer require to transform 198 000 J of energy in 15 min? T/I [ans: 220 W]

As you can see from **Table 1**, some devices need very little power, while others need significant amounts of power. Consider all the devices in all the homes in Ontario—a lot of electrical power is needed every day. Employees at the power plant monitor power needs and generate power "on demand." For example, on a hot summer day, more power is needed for air conditioning. When more power is needed, the power plant employees increase power generation up to the maximum capability. If no more can be generated, then the electricity has to be purchased from somewhere else, such as the United States. As a last resort, the power plant employees may shut down the power to a neighbourhood for a short time. Short temporary interruptions to the electricity supply are called "brownouts." Brownouts can cause harm to electrical devices because of the rapid change in electrical power. Power is generated on demand because there is no practical method of storing the electrical energy. Batteries are impractical because of the large number that would be needed.

Table 1 Power Ratings

Electrical device	Power rating (W)
MP3 player	0.4
charger for an MP3 player	120
laptop computer	20–75
52 in. LCD TV	220
50 in. plasma TV	380
central air conditioner	7000
stove	6000–10 000

Measuring Electrical Energy

Electrical energy is measured in units of **kilowatt hours** (kWh) because the joule (J) is sometimes too small to be a convenient measurement. One kilowatt hour is equal to 3.6 million joules. A typical home in Ontario uses 1000 kWh of electrical energy each month.

kilowatt hour (kWh) measure of electrical energy

The kilowatt hour is a useful unit of measurement for homes, but when describing the electrical energy generated by a power plant we use megawatt hours (MWh). In 2007, Ontario generated over 158 million megawatt hours of electrical energy. That is approximately 12 100 kWh per person for the year. In general, Canadians use a lot more electrical energy than people in some other parts of the world. By comparison, residents of Chad (a country in Africa), use 9 kWh per person per year. In the following Tutorial, you will determine how much energy a light bulb transforms over a given time period in units of kilowatt hours.

Tutorial 2 Calculating Energy

In the following Sample Problem, we will rearrange the equation $P = \dfrac{\Delta E}{\Delta t}$ to determine how much energy is transferred in a halogen light bulb.

Sample Problem 1

Calculate the energy needed by a 35 W halogen light bulb that operates for 240 h. Give your answer in both joules and kilowatt hours.

Given: $P = 35\ \text{W}$; $\Delta t = 240\ \text{h}$

Required: ΔE

Analysis: $P = \dfrac{\Delta E}{\Delta t}$

$$\Delta E = P\Delta t$$

Solution: Convert time to seconds to get the answer in joules:

$$\Delta t = 240\ \cancel{\text{h}} \times \frac{3600\ \text{s}}{1\ \cancel{\text{h}}}$$

$$= 864\,000\ \text{s}$$

$$\Delta E = (35\ \text{W})(864\,000\ \text{s})$$

$$= 3.024 \times 10^7\ \text{J} \quad \text{(two extra digits carried)}$$

To find the answer in kilowatt hours, convert from joules:

$$3.024 \times 10^7\ \cancel{\text{J}} \times \frac{1\ \text{kWh}}{3.6 \times 10^6\ \cancel{\text{J}}} = 8.4\ \text{kWh}$$

Another way of solving the problem is to convert the power from 35 W to kilowatts and then use the power equation:

$$35\ \cancel{\text{W}} \times \frac{1\ \text{kW}}{1000\ \cancel{\text{W}}} = 0.035\ \text{kW}$$

$$\begin{aligned} \Delta E &= P\Delta t \\ &= (0.035\ \text{kW})(240\ \text{h}) \\ \Delta E &= 8.4\ \text{kWh} \end{aligned}$$

Statement: The halogen light needs 3.0×10^7 J or 8.4 kWh of energy to operate for 240 h.

Practice

1. A compact fluorescent light bulb operates with 7.0 W of power. Calculate the energy it needs to provide light for 24 h. Answer in joules. T/I [ans: 6.0×10^5 J]
2. Convert your answer in Question 1 to kilowatt hours. T/I [ans: 0.17 kWh]

Energy Efficiency and Power Plants

Non-renewable sources of energy are running out, and our current renewable sources are not sufficient to meet the demand. To meet the demand for electrical energy, we can use two approaches: conservation and generating energy more efficiently. To conserve energy, newer devices are designed to use less electrical energy than older ones, and people are developing a more critical attitude to the use of electrical energy. At the same time, we have to find ways to improve the efficiency of power plants.

Recall from Chapter 5 that efficiency is a measure of how well a technology transforms energy. Power plants must transform the source energy into electrical energy, a process that is not 100 % efficient (**Table 2**). Engineers can design ways of preventing energy losses during energy transformation. For example, an engineer can improve the efficiency of a coal-fired plant by directing the steam into pipes and increasing its pressure, allowing it to reach much higher temperatures. The higher temperatures make the transfer of energy more efficient. The temperature of the steam in a modern coal-fired plant can reach 600 °C, and the pressure can be up to 250 times as great as atmospheric pressure.

CAREER LINK

Power engineers ensure the safe and efficient operation of generators at power plants. To find out more about power engineers,

GO TO NELSON SCIENCE

Table 2 Efficiency of Power Plant Technologies

Power plant technology	Average efficiency*	Example of a power plant in Ontario (power-generating capability)	Notes on efficiency
hydro	85 %	Sir Adam Beck II (1499 MW)	Not all of the water is stopped, so some energy is lost.
fossil fuel	45 %	Nanticoke (3640 MW)	Thermal energy is developed from a combustion reaction to produce steam, but not all of the thermal energy is captured.
wind	40 %	Huron Wind Farm (9 MW from 5 turbines)	Not all of the wind is captured, so some energy is lost.
nuclear	35 %	Darlington Nuclear Plant (3500 MW)	Thermal energy is developed from a nuclear reaction to produce steam, but not all of the thermal energy is captured.
solar	15 %	Sarnia Solar Farm (20 MW)	Much of the sunlight is converted into thermal energy instead of electrical energy.

*Efficiency of the power plant technology in general, not the particular technology used in the sample power plant

UNIT TASK BOOKMARK

You can apply what you have learned about electrical energy, efficiency, and power plants to the Unit Task on page 622.

When considering the pros and cons of sources of energy and power plant technologies, we must consider both environmental aspects and the potential impacts on society. Environmental aspects include the ease of obtaining the source of energy, the dependability of the source of energy, the location of the power plant, atmospheric emissions, and other forms of pollution. Impacts on society include the financial cost of building and operating the power plant, employment opportunities in the plant, safety, and the effects on nearby communities.

Research This

Power Plant Efficiency

Skills: Researching, Communicating

SKILLS HANDBOOK **A5.1**

As you can see from Table 2 on the previous page, the efficiency of power plants varies widely. Having more efficient power plants means using fewer resources and spending less money to operate the power plant. Note that efficiency can describe how well processes work. Operational efficiency describes how much time something is working compared to how much time it is not working. Thermal efficiency describes how much thermal energy is used to perform a task compared to how much thermal energy is wasted.

1. Choose one type of electricity generation technology and find some current efficiency numbers. Be sure to focus on thermal efficiency and not operational efficiency.
2. Research to find out why some power plants have higher efficiencies than others.

A. State which electricity generation technology you chose and give the thermal efficiency. T/I

B. What design feature has most improved the efficiency of this technology? T/I A

C. How could implementing that design feature improve other plants using a similar technology? T/I

D. Write a one-page report on what could be done to improve the efficiency of other types of power plants. C A

GO TO NELSON SCIENCE

11.1 Summary

- Mechanical energy, thermal energy, and radiant energy are transformed into electrical energy in power plants.
- Electrical power is the rate at which electrical energy is generated or transformed.
- Electrical energy is measured in units of kilowatt hours (kWh) for homes and megawatt hours (MWh) for power plants.
- Power plant technologies vary in efficiency, and each has impacts on the environment and society.
- Improving the efficiency of power plants can decrease our use of resources.

11.1 Questions

1. Write a statement that uses the word “electricity” incorrectly (try to think of an example that you have heard). What does the word “electricity” refer to? K/U C
2. A car battery transfers 19 200 J of energy to the starter in 2.0 s when you turn the key to start the engine. Calculate the power of the starter. T/I
3. A 1200 W microwave oven transforms 1.8×10^5 J of energy while reheating some food. Calculate how long the food was in the microwave. Answer in minutes. T/I
4. A plasma television requires 380 W to operate. A family watches television for 110 h in one month. Calculate how much energy is needed. Answer in joules and kilowatt hours. T/I
5. How much television does the family in Question 4 watch in a year? Calculate how much energy is needed to power the television annually. Answer in joules and kilowatt hours. T/I
6. Look at Table 2 on page 506 and choose a power plant technology that you found particularly interesting. What was your reaction to reading about its efficiency? Write a few sentences about your reaction. C A

11.2 Explore an Issue in Generating Electricity

SKILLS MENU

- Defining the Issue
- Researching
- Identifying Alternatives
- Analyzing
- Defending a Decision
- Communicating
- Evaluating

Clean Coal Technology

Coal is an abundant and inexpensive fuel that is used all around the world. Many countries rely heavily on burning coal to generate electrical energy. However, burning coal emits large quantities of carbon dioxide (a key contributor to global warming), sulfur dioxide (which causes acid rain), nitrous oxide (which leads to the formation of smog), and other air toxins and particulates.

In recent years, new "clean coal" technologies have reduced some of the negative effects of burning coal. Coal-fired power plants typically have a tall smokestack that releases gases called "flue gases" as the coal is burned. "Scrubber" technologies can remove sulfur oxides from the flue gases before they are released into the atmosphere. Another way to lessen the negative effects of burning coal is to turn the coal into gases that are rich in hydrogen and carbon monoxide and then burn them. This process is called "coal gasification" and it helps improve the burning process so that less waste is produced. Some coal plants use chemical reactions to remove harmful minerals from the coal before burning.

Figure 1 This coal power plant in Spremberg, Germany, uses carbon capture and storage.

Controlling or preventing the release of carbon dioxide from burning coal is the biggest challenge. Engineers have proposed many solutions to this problem, including carbon capture and storage (CCS) (**Figure 1**). CCS technologies capture the carbon dioxide and compress it. The carbon dioxide is then stored deep underground as a gas, dissolved in Earth's oceans, or reacted chemically to produce metal carbonates.

Increasing the efficiency of coal power plants is also being investigated. Improving efficiency could lead to lower costs and more electrical energy generated per kilogram of coal. So, for the same amount of electricity produced, less coal is used and therefore less pollution is produced.

Coal plants are often portrayed as "dirty." There has been a movement toward alternative power generation methods that are "clean," such as wind and solar power generation. Should we continue to research improving coal power generation, or should we abandon it and move toward alternatives?

The Issue

The province of Ontario is considering upgrading a coal-fired power plant in your community to use clean coal technology. A local concerned citizens group is urging the town to instead consider spending the money to support and use alternative methods of power generation. A town hall meeting is being held to hear the different points of view.

ROLE

Pick one of the following stakeholders and present your decision from their perspective: community member, power plant executive, power plant employee, government minister, manufacturer of clean coal technology, coal industry representative, environmentalist, alternative power plant executive.

AUDIENCE

Your teacher and classmates will represent local citizens attending a town hall meeting about the proposed plant upgrade.

Goal

To convince the citizens of your community to either upgrade the coal-fired plant or spend money on alternative methods of power generation

Research

SKILLS HANDBOOK A5.1

You should research specific details related to the role you have chosen. You might want to research the following examples:

- CCS is currently in use at a power plant in Spremberg, Germany (Figure 1). Find out what people are saying about this development. Be sure to research the efficiency of this method.
- The government of Alberta has dedicated $2 billion to CCS technology. Find out about some of the proposed projects.
- Ontario is planning a wind farm on the shores of Lake Ontario, and a large solar power plant is proposed for Sarnia. Research these alternatives to help you make a decision.

WEB LINK

To learn more about CCS technologies and alternatives,

GO TO NELSON SCIENCE

Identify Solutions

You may wish to consider the following factors to help identify options for your community:

- How efficient are coal-fired plants that use CCS compared to wind power and solar power?
- What financial costs and benefits are associated with CCS plants compared to wind and solar power generation?
- What kinds of impacts (positive and negative) does each type of power generation have on the community? Consider employment opportunities, environmental effects, effects on wildlife and habitat, noise, and pollution.

Make a Decision

Decide whether you think CCS technology is a reasonable and workable tool for upgrading the coal-fired electricity generating plant. Are there disadvantages to CCS technology? Should the town develop other forms of electricity generation instead?

Communicate

- Prepare a graphic organizer from the perspective of your role. Your graphic organizer should be designed to convince local citizens to support your position. You must be able to support your arguments and answer questions about the information you have collected. Your graphic organizer must highlight both advantages and disadvantages. Graphic organizers can be t-charts, SWOT (strengths, weaknesses, opportunities, and threats) tables, flow charts, or any other suitable format.
- Post your graphic organizer for others to see. Review your classmates' graphic organizers. Make note of any arguments for and against the CCS plant. You may find some points that you have not considered.
- Find a partner in your class who chose the opposite position to you and discuss. After the discussion, write a one-page reflection focusing on which of you had better arguments.

Plan for **Action**

Suppose that an article is presented in the local newspaper on the proposed clean coal plant. Write a letter to the editor stating your views. The letter should focus on arguments that you thought were strong. Plan a way to get people in your community to side with you and help your voice be heard.

11.3 Electric Potential Difference

In Section 11.1, you learned that electrical energy is generated by transforming energy in a power plant. The amount of electric energy generated can be increased by adjusting the variables involved. For example, in a nuclear power plant, the reactor can be run at a higher temperature to produce more thermal energy. This extra thermal energy can be used to generate more electrical energy. In a wind turbine generator, the blades can be positioned so that they rotate faster for the same amount of wind. This extra kinetic energy can be used to generate more electrical energy. How is electrical energy transferred?

Figure 1 Electricity travels from the power plant to your home along transmission lines.

Electrical Energy Transfer

Electrical energy is transferred from a power plant to your home through conducting wires called transmission lines. Transmission lines radiate out from the power plant in many directions across the province and the country (**Figure 1**). The wires are made from a metal, usually aluminum. In a metal, electrons are free to move and they are the most important part of the conducting wires because they provide the means for the transfer of electrical energy. Without these freely moving electrons, the electrical energy could not be transferred from the power plant to your home.

In Chapter 5, you learned that there are different forms of energy, one of which is potential energy. Electric potential energy results from the separation of electrons, which are negatively charged, so they repel each other. To overcome this force and push the electrons closer together, energy must be transferred to the electrons, increasing their electric potential energy. The closer electrons are pushed together, the greater is the electric potential energy. The movement of electrons therefore requires a change in energy.

Mini **Investigation**

Modelling Electric Potential Energy

Skills: Performing, Observing, Analyzing, Communicating

SKILLS HANDBOOK **A2.1, A2.4**

It is difficult to imagine what electrons are doing in a wire. You cannot "see" electrical energy. In this investigation, you will use a Newton's cradle (**Figure 2**) to model electrical potential energy and the transfer of that energy through a wire. Only observe the initial forward motion of the spheres; ignore the back and forth motion. The spheres in the middle represent the electrons in the wire, and the spheres on the ends represent electric potential energy.

Equipment and Materials: Newton's cradle

1. Raise one of the end spheres slightly and let it go. Record your observations of what happens to the spheres on each end as well as the spheres in the middle.
2. Repeat Step 1, but this time raise the end sphere higher before you let it go. Record your observations.
3. Pull the middle spheres to one side so that they are not suspended between the end spheres. Raise one end sphere and then release it. Record your observations.

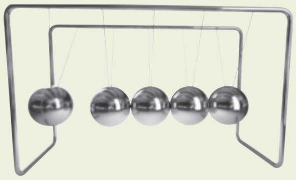


Figure 2 Newton's cradle

A. The height by which you raised the end sphere represents the amount of electric potential energy. How did the amount of electric potential energy change the outcome? T/I

B. How did the speed of the energy transfer compare to the speed of the middle spheres? T/I

C. How did moving the middle spheres to one side affect the results of the investigation? T/I

D. This is a model of electric potential energy and its transfer. State one possible limitation of this model. T/I

Electric Potential Difference

electric potential the amount of electric potential energy associated with charges

Electric potential is the measurement of the electric potential energy associated with charges (in this case, electrons). You can think of electric potential as the amount of energy needed to move a quantity of electrons closer to one another. In a circuit, electrons are closely packed together in the conducting wires. Moving the electrons closer together increases their electric potential. The more work that is done to move the electrons closer together, the larger is the electric potential.

Electric potential measures both the electrical energy and the quantity of electrons. The unit for measuring electric potential is the joule per coulomb (J/C). The joule (J) is a measurement of the electric potential energy, and the coulomb (C) is a measurement of the number of electrons or amount of charge. This unit is more commonly known as the volt (V), in honour of scientist Alessandro Volta. 1 J/C is equal to 1 V.

electric potential difference (*V*) the change in electric potential energy associated with charges at two different points in a circuit

Instead of measuring electric potential at one point in a circuit, it is more useful to measure the difference in electric potential between two different points in the circuit. Differences in electric potential exist because energy is transformed in an electric circuit. For example, the electrons at a battery have a different amount of electric potential energy than the electrons at a light bulb. This gives rise to a quantity called the electric potential difference. **Electric potential difference** is the difference in electric potential energy associated with a coulomb of charge at two different points in a circuit. Electric potential difference is also referred to as voltage (*V*). A positive electric potential difference is sometimes called a voltage gain. A negative electric potential difference is sometimes called a voltage drop. Electric potential difference can be represented by the following equation:

$$V = \frac{\Delta E}{Q}$$

where V = electric potential difference (joules per coulomb or volts), ΔE = change in electric potential energy (joules), and Q = the amount of charge (electrons) (coulombs). In the following Tutorial, you will use this equation to calculate the electric potential difference in electric devices.

Tutorial 1 Using the Electric Potential Difference Equation

Electric potential difference can be calculated given the change in electric potential energy in joules and the amount of charge (electrons) in coulombs. In the following Sample Problem, we will calculate electric potential difference.

Sample Problem 1

Calculate the electric potential difference between the negative and positive terminals of a battery if 1500 J of electric potential energy is transformed to move 125 C of charge between the terminals.

Given: $\Delta E = 1500\text{ J}$; $Q = 125\text{ C}$

Required: V

Analysis: $V = \frac{\Delta E}{Q}$

Solution:
$$\begin{aligned} V &= \frac{\Delta E}{Q} \\ &= \frac{1500\text{ J}}{125\text{ C}} \\ V &= 12\text{ V} \end{aligned}$$

Statement: The electric potential difference of the battery is 12 V.

Practice

1. A computer processor chip transforms 120 J of energy while moving 52 C of electrons. Calculate the electric potential difference of the chip. T/I [ans: 2.3 V]

Measuring Electric Potential Difference

voltmeter electrical device that measures electric potential difference

CAREER **LINK**

For information about becoming a computer technician, automotive repair technician, or electrician,

GO TO NELSON SCIENCE

A **voltmeter** is used to measure electric potential difference in circuits. A computer technician uses a voltmeter to see if the power supply to a computer is working properly. If your car does not start when you turn the key, an automotive repair technician uses a voltmeter to test if the starter motor is working properly. An electrician uses a voltmeter to test if a circuit is "live," so it can be shut off before work begins. At home, you can use a voltmeter to test if a battery has enough electrical energy to make a flashlight work.

In Grade 9, you learned that circuits can have one complete path (series circuits) or more than one complete path (parallel circuits). The two types of circuits are shown in **Figure 3**. Voltmeters only work accurately if they are connected in parallel in the circuit. To connect in parallel, you must create a separate path for the electrons to follow in the circuit. This separate path allows only a very small amount of electrical energy to go into the meter. The majority of the electrical energy is in the rest of the circuit. The circuit symbol for a voltmeter is —(V)—.

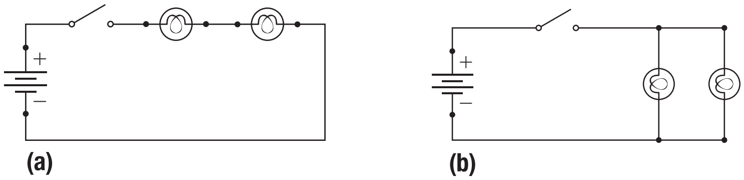


Figure 3 (a) Series circuit (b) Parallel circuit

Circuits contain sources of electrical energy (such as a battery or power supply), connecting wires, control devices (such as a switch), and loads (such as a lamp or a motor). You can think of sources as the parts of the circuit that cause an increase in the electric potential, or a voltage gain. You can think of loads as the parts of the circuits that cause a decrease in the electric potential, or a voltage drop (**Figure 4**).

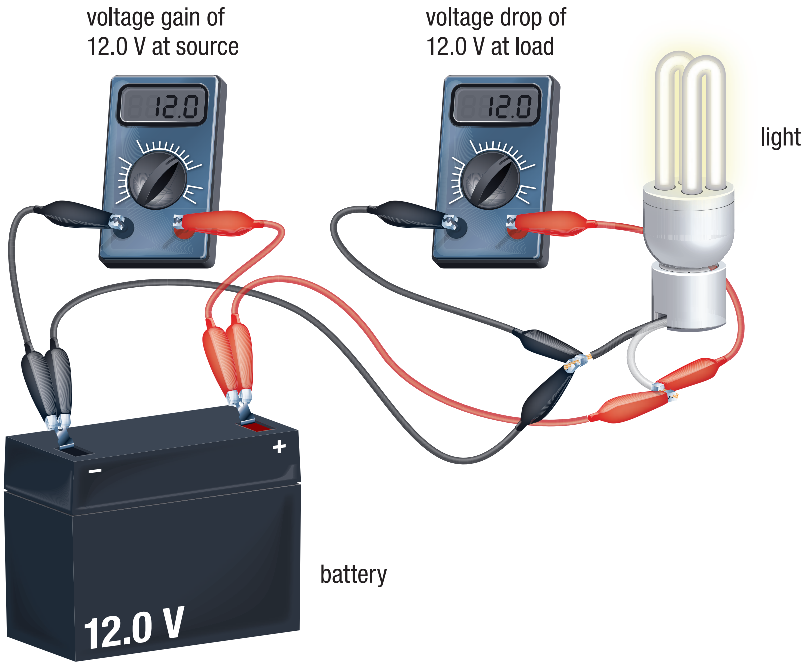
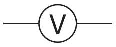


Figure 4 Sources cause an increase in electric potential (voltage gain), and loads cause a decrease in electric potential (voltage drop).

In an ideal circuit, the connecting wires and control devices do not affect the amount of electric potential and therefore do not cause a voltage drop. However, in a real circuit, the connecting wires and control devices can cause a voltage drop.

11.3 Summary

- Free electrons that are able to move are essential for the transfer of electrical energy.
- Electric potential is a measure of how much electric potential energy is associated with charges.
- Electric potential difference, or voltage, indicates the difference in electric potential energy of the charges (electrons) between two points in a circuit.
- The equation for electric potential difference is $V = \frac{\Delta E}{Q}$.
- Electric potential difference is measured in joules per coulomb (J/C) or volts (V).
- The amount of charge or number of electrons (Q) is measured in coulombs.
- Voltmeters measure electric potential difference and are connected in parallel in a circuit. They have the circuit symbol .
- Sources of electrical energy cause an increase in the electric potential (voltage gain), whereas loads cause a decrease in the electric potential (voltage drop).

11.3 Questions

1. Calculate the electric potential difference if 1750 J of electric potential energy is transformed to move 3.1 C of electrons. T/I
2. Calculate the energy transformed in a 15 V adapter that has 0.075 C of electrons moving through it. T/I
3. How much charge is travelling through a 3.7 V cellphone that transforms 6.0 J of electrical energy? T/I
4. (a) A 7.0 W CFL bulb is on for 2.5 h. During that time, 525 C of electrons move through the bulb. Determine the electric potential difference of the CFL bulb. (Hint: you will need to use the power equation from Section 11.1.)
   (b) Each coulomb has 6.2×10^{18} electrons in it. Calculate the number of electrons that were moved through the CFL bulb in part (a). T/I
5. In medical television shows, doctors use defibrillators to try and establish a normal rhythm in a patient's heart. To do this they shock the heart with approximately 130 J of electrical energy at an electric potential difference of 710 V. Determine the amount of charge that is delivered to the heart. T/I
6. A student connects a circuit that contains a battery, a switch, and an LED lamp. K/U
   (a) In which part(s) would you expect to observe a voltage gain, and in which part(s) would you expect to observe a voltage drop?
   (b) Is there any part of the circuit where you would expect no voltage drop or gain? Explain your reasoning.
7. Do the following electrical devices cause an increase or a decrease in electric potential? State whether each device causes a voltage gain or a voltage drop. K/U
   (a) power plant
   (b) digital camera
   (c) game console
   (d) wind turbine
   (e) solar panel
   (f) calculator
8. Identify what is wrong with each of the following statements, and rewrite it so that it is correct: K/U C
   (a) A voltmeter must always be connected in series.
   (b) A series circuit has more than one complete path.
   (c) Connecting a voltmeter in series will allow only a small amount of electrical energy to travel through it.
   (d) A parallel circuit can only have two complete paths.
   (e) A complete circuit contains a source of electrical energy and a load.
9. Redraw the circuit diagrams from Figure 3 on page 512 with a voltmeter connected properly to the first lamp. T/I

Is Benjamin Franklin to Blame?

ABSTRACT

Benjamin Franklin (1706–1790) was a well-known American scientist who is most known for his kite experiment, in which he flew a kite during a lightning storm to investigate the nature of electricity. He decided that when describing electricity, an excess of electricity (or the charge that makes up the electricity) is positive and a deficit of electricity is negative. This convention of describing electricity became entrenched in science, but 150 years later it was found to be incorrect. Benjamin Franklin cannot be blamed for his mistake because his conclusion was reasonable. Today we use two conventions for modelling electricity—the conventional current model and the electron flow model.

The Life of Benjamin Franklin

Benjamin Franklin was born in 1706. He was formally educated for only two years. When he was 10, he left school and started to work for his father making soap. At the age of 13, he was bored with making soap and started working with his brother James as a printer, which eventually led to a career in writing and publishing newspapers. He retired at the age of 42 and started to pursue scientific knowledge (**Figure 1**). He is credited with founding the American Philosophical Society for "promoting useful knowledge" in the form of journals that include articles on the history of science.

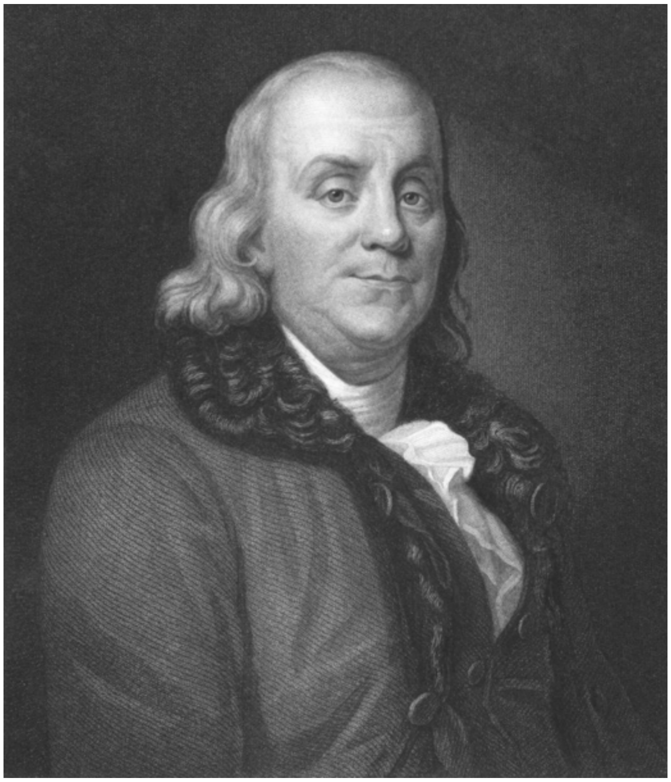


Figure 1 Benjamin Franklin's interest in science started when he was 42.

Developments in Electricity Knowledge

In the early to mid-1700s, the understanding of electricity was increasing rapidly. In 1729, English scientist Stephen Gray was the first to demonstrate the conduction of electric charge through metals and the insulation of charge in non-metals. Scientists of the time believed that electricity was a fluid called "electric effluvia." Gray was not formally trained as a scientist; he was self-taught and performed well-regarded controlled experiments. He used glass tubes as insulating objects. It was these glass tubes that got Benjamin Franklin interested in electricity. After seeing some experiments with electricity, Franklin declared in a letter, "For my own part, I never was before engaged in any study that so engrossed my attention and my time as this has lately done."

In 1752, Benjamin Franklin performed his famous kite experiment when he flew a kite (**Figure 2**) during a lightning storm. He hoped that lightning would strike near the kite. The lightning did not strike the kite directly; that would have immediately destroyed the kite and seriously harmed, or killed, him.

Franklin hoped to store some of the lightning in a key and a Leyden jar (a glass jar with electrodes used to hold static charge). A lightning strike did occur nearby. When he approached the Leyden jar, he accidentally reached out and touched the key with his knuckle and felt an electric shock. This showed that the key had been charged, proving that lightning is a form of electricity.

Experiments showed that there were two distinct types of electricity. Rubbing glass with silk produced one type of charge, but rubbing amber with fur produced a different type of charge. If two pieces of charged glass were brought together, they repelled each other. If a piece of charged amber and a piece of charged glass were brought together, they attracted each other. These experiments led Franklin to believe that electricity was a mysterious force that diffused through most substances and came in two forms—positive and negative. Here is where some people want to blame Benjamin Franklin for getting it wrong. Franklin thought that excess electricity was positive and that a deficit of electricity was negative—a very reasonable assumption. This was a reasonable assumption that became the basis of the convention for describing the movement of charge for many years.

Knowledge and technology with respect to electricity continued to develop. The next 100 years saw the development of the battery, the electric motor, the incandescent light bulb, and, in 1882, the first power plant. It was not until 1897 that J.J. Thomson discovered the electron using a cathode ray tube. His discovery of the electron also led him to describe some of the properties of electrons and one of those properties was that the electron is negatively charged.

The discovery that the electron is negatively charged required a rethinking of what was meant by excess electricity. After over 150 years of research and technological development in the field of electricity, it was found that Franklin's idea that excess electricity is positive was incorrect.

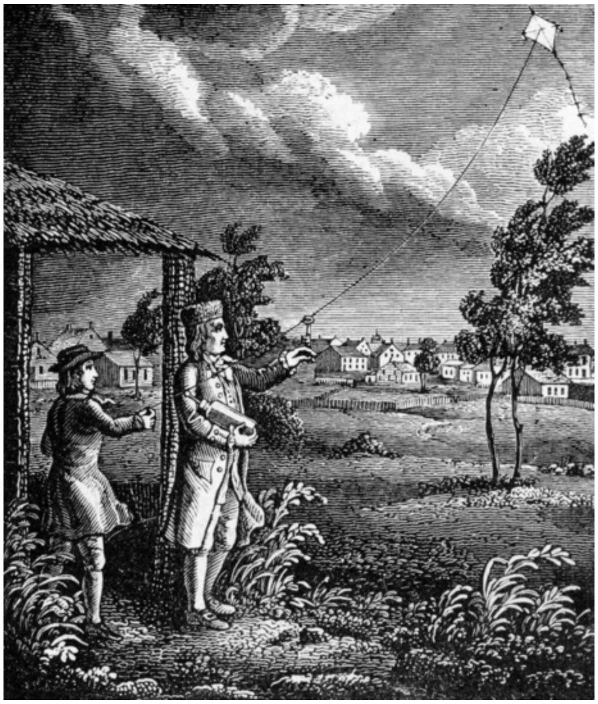


Figure 2 Benjamin Franklin proved that lightning is a form of electricity.

Do We Need to Correct the Mistake?

Do we change a century and a half of books and studies? No. Instead, two conventions were developed, providing two ways to describe the direction of the movement of charge.

One convention is to consider the movement of charge through an electrical circuit as moving from the positive side to the negative side. That is how it was understood for over 150 years. We call the movement of charge from positive to negative "conventional current." The other convention is to view the movement of electrons from negative to positive. This is the way the movement of charge really goes and is called "electron flow."

Is Benjamin Franklin to be blamed for his choice? In dealing with electricity and metal conductors, he did misstate the direction of the movement of charge. However, there are many instances where positively charged particles move. In fact, in a wet-cell battery, positive charges called ions, as well as the negatively charged electrons, move. Lightning also includes the movement of both positive and negative charges.

Conclusion

We cannot blame Benjamin Franklin for making a hypothesis. It is the nature of science to analyze data and observations and then draw a reasonable conclusion. Although Franklin's conclusion was incorrect, it was reasonable. When new information became available, scientists changed their thinking based on new data and observations. In the end, we now have two conventions for modelling electricity—conventional current and electron flow.

Further Reading

Krider, E.P. (2006). Benjamin Franklin and lightning rods. *Physics Today, 59.1*, 42–48.

Wills, S., & Wills, S.R. (2004). Benjamin Franklin and the electricity of lightning. In *Meteorology: Predicting the Weather* (pp. 30–45). Minneapolis: Oliver Press.

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11.4 Questions

1. Did any part of Benjamin Franklin's life surprise you? Explain why. C A
2. In the article, it states that scientists believed that electricity was a fluid. Does this seem reasonable? Explain why. C
3. The kite experiment is famous. Why do you think this is the case? C
4. Why do you suppose knowing whether electricity flowed from positive to negative or from negative to positive did not prevent scientists from developing electricity technologies? K/U C
5. (a) Write a description of conventional current and electron flow in your own words.
   (b) Draw a diagram of a circuit, and show the positive and negative parts of the source. Use arrows to indicate the direction of charges for each convention. K/U C

11.5 Electric Current

The movement of electrons (an electric current) is required for an electrical device to operate. Electric current is responsible for the transfer of electrical energy along a conducting wire. Your computer, refrigerator, stove, and battery charger simply would not work without moving electrons in conducting wires.

Direct Current

direct current (DC) the movement of electrons in only one direction

Direct current (DC) is the flow of electrons in only one direction through a circuit. The electrons flow from the negative terminal of the source of electrical energy and travel through the conducting wires toward the positive terminal.

The outer electrons in the atoms of a metal conductor are not tightly held to their nuclei; rather, they move around randomly and are considered "free electrons." When a source of electrical energy (for example, a battery) is supplied to a circuit, free electrons will move in one direction through the conductor (**Figure 1**). This movement of the free electrons is the direct current. The more free electrons that are moving in one direction, the greater is the direct current.

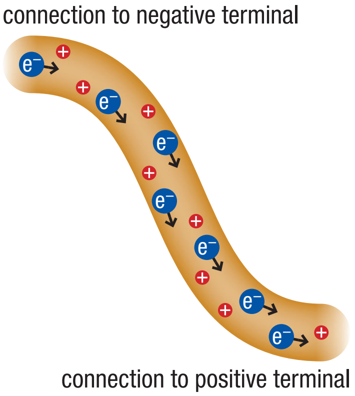

connection to negative terminal
e⁻
+
connection to positive terminal

Figure 1 Direct current showing the electrons moving in one direction only. The positive charges represent the nuclei of the atoms and do not move.

The first sources of electrical energy were similar in design to batteries and all produced a direct current. In 1820, French physicist André-Marie Ampère performed experiments on direct currents in wires. He was interested in measuring the *intensity* of the current, which is why today we use the symbol I to represent electric current. In recognition of his contributions to the understanding of electric current, the unit of measurement for electric current is called the ampere (A). The equation that describes the amount of electric current is

$$I = \frac{Q}{\Delta t}$$

where I = current (A), Q = amount of charge (C), and Δt = time interval (s). One coulomb of charge (or electrons) passing one point every second in a circuit is equivalent to one ampere. Therefore, 1 A = 1 C/s. In illustrations of current, we often depict only a few electrons. However, a coulomb of electrons is 6.2×10^{18} electrons. So a current of 1 A means over 6 billion billion electrons moving past a point each second.

Tutorial 1 Using the Current Equation

When you are given the amount of charge and the change in time, you can use the equation $I = \frac{Q}{\Delta t}$ to find the amount of current. We will apply the current equation in the following Sample Problem.

Sample Problem 1

Calculate the amount of current through a wire that has 0.85 C of electrons passing a point in 2.5 min.

Given: $Q = 0.85$ C; $\Delta t = 2.5$ min

Required: I

Analysis: $I = \frac{Q}{\Delta t}$

Solution: Convert time to seconds to get the answer in coulombs per second, or amperes:

$$\Delta t = 2.5\,\cancel{\text{min}} \times \frac{60\text{ s}}{1\,\cancel{\text{min}}}$$

$$\Delta t = 150\text{ s}$$

$$I = \frac{Q}{\Delta t}$$
$$= \frac{0.85\ \text{C}}{150\ \text{s}}$$
$$I = 0.0057\ \text{A}$$

Statement: The current is 0.0057 A.

Practice

1. What is the current travelling through a cellphone charger when 0.20 mC of electrons pass a point in 0.75 min? Answer in amperes and microamperes (μA). T/I [ans: 4.4×10^{-6} A; 4.4 μA]
2. How many electrons, measured in coulombs, result from a current of 15 A for 24 h? T/I [ans: 1.3×10^{6} C]

Effects of Current on Your Body

The nerve cells in your body communicate with each other by creating very small electric currents. If a larger current is transmitted through your body it can overload your nervous system. By touching a wire with a current flowing through it, you can affect the current in your body (**Table 1**). Muscles will contract and you may not be able to let go of the wire. The electric current will also cause burns, because some of the electrical energy will be transformed into thermal energy. An electric shock can burn tissue deep inside the body, not just on the surface.

Table 1 Effects of Current on Your Body

Direct current (A)	Sensation
0.0008	slight tingling
0.051	painful but can still control muscles
0.064	painful but can let go of wires
0.075	severe pain with difficulty breathing
0.50	possible heart fibrillation

Measuring Electric Current

An **ammeter** is a device that measures electric current. An electrician uses an ammeter to determine the current in a home circuit. Too much current can be dangerous because moving electrons cause wires to heat up. Ammeters must be connected in series in a circuit (**Figure 2**), so that all the electrons flowing through the wire also have to flow through the ammeter, giving an accurate reading of the current. If the ammeter were connected in parallel, there would be more than one path for the current to flow along: one path would be into the circuit while the other path would be through the ammeter. You would not be sure how much of the current went through the path. The symbol for an ammeter is —Ⓐ— .

ammeter electrical device that measures electric current; must be connected to the circuit in series

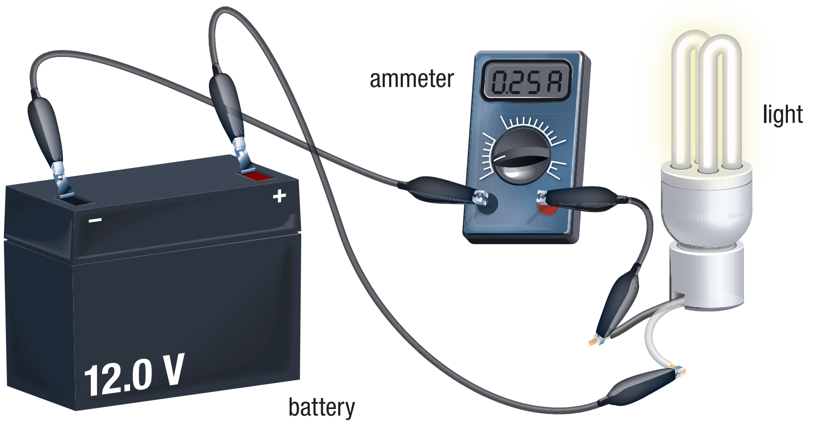


Figure 2 An ammeter is connected in series to measure electric current.

Mini Investigation

How Much Current Can a Lemon Produce?

Skills: Performing, Observing, Analyzing SKILLS HANDBOOK A3.2

A lemon cell is a source of electrical energy. Other fruits, vegetables, and juices will also work. The foods just need to contain an acid, which acts as an electrolyte or conducting solution. You also need two electrodes (conductors) made from two different materials. When you connect the lemon cell to an ammeter, you will be able to measure the current that is produced. Alternatively, you could use a galvanometer, which is essentially a more sensitive ammeter.

Equipment and Materials: zinc strip; copper strip; ammeter with a milliamp scale; 6 or more alligator clip leads; LED; lemons

1. Construct a lemon cell by inserting a zinc electrode strip and a copper electrode strip into the lemon. Connect the negative terminal of an ammeter (set to the milliamp scale) to the zinc strip using an alligator clip lead. Then connect the positive terminal to the copper strip (**Figure 3**).
2. Read the scale on the ammeter and record your measurement. Now connect a load to the lemon cell. The load can be an LED, for example.

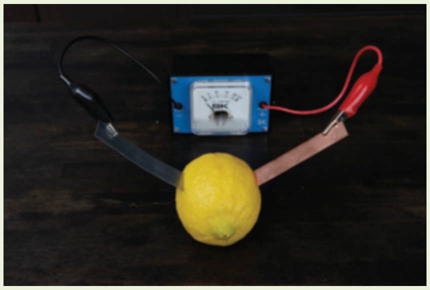


Figure 3

3. Read the scale from the ammeter with the load connected, and record your measurement.
4. Try connecting more lemon cells in series and record the effect on the load and the reading on your ammeter.

A. What is the difference in current measurements between Steps 2 and 3? T/I

B. What is the effect of connecting more lemon cells in series on the current and the brightness of the LED? T/I

11.5 Summary

- Direct current is the flow of electrons in one direction only.
- The symbol for current is I and current is measured in units of amperes (A).
- The equation that describes current is $I = \frac{Q}{\Delta t}$.
- An ammeter is used to measure current in a circuit and must be connected in series. An ammeter has the circuit symbol —Ⓐ— .

11.5 Questions

1. What is direct current? In which direction does current go according to the electron flow convention? K/U
2. What is the current if 2.5 C of charge (electrons) passes a point in a circuit in 4.6 s? T/I C
3. Calculate the amount of charge travelling through a car battery when a current of 800.0 A is produced for 1.2 min. T/I
4. For how long can a battery produce a current of 250 mA if 1.7×10^2 C of charge passes through it? Answer in seconds and minutes. T/I
5. LED lights require less power than incandescent lights. Calculate the time required for 150 μC of charge (electrons) to pass through an LED light if the current is 0.21 mA. T/I
6. Batteries have a rating system that includes the current and the time. A rechargeable AA battery might have a rating of 2650 mAh. That is, the battery can produce a current of 2650 mA for 1 h before it is depleted. For how long could it produce a current of 883 mA? T/I
7. A student connects an ammeter in parallel and notices that the reading is a very large number. Provide a possible explanation for the high reading. K/U C
8. Is it possible to produce an electric current in a material that does not have any free electrons? Explain your answer. K/U
9. Refer to Table 1 on page 517. Electricians routinely work on household circuits that have current ratings of 15 A or more. Why do you suppose they turn off the power before working on the circuit? K/U

Kirchhoff's Laws

In 1845, German physicist Gustav Kirchhoff (**Figure 1**) investigated circuits. He was able to describe two important laws: one law describes the electric potential difference and the other the electric current in circuits. When engineers design circuits, they use Kirchhoff's laws to understand what will happen to the voltage and current when the circuit is in use.

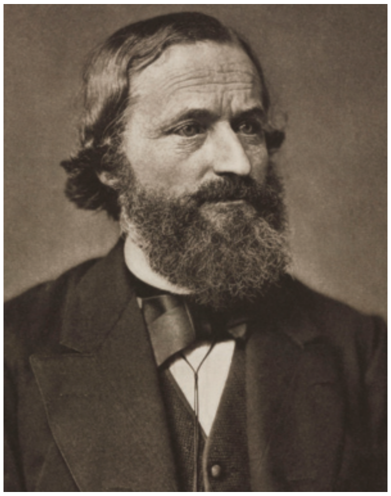


Figure 1 Gustav Kirchhoff developed laws that describe voltage and current in circuits.

Kirchhoff's Voltage Law

Recall that electric potential difference can also be referred to as voltage. **Kirchhoff's voltage law (KVL)** is stated as follows:

Kirchhoff's Voltage Law

In any complete path in an electric circuit, the total electric potential increase at the source(s) is equal to the total electric potential decrease throughout the rest of the circuit.

Kirchhoff's voltage law (KVL) in any complete path in an electric circuit, the total electric potential increase at the source(s) is equal to the total electric potential decrease throughout the rest of the circuit

Electric potential increases at the source, so there must be an electric potential difference or voltage gain across the source. Similarly, electric potential decreases across the loads in the circuit, so there must be an electric potential difference or voltage drop. The sum of the voltage gains and drops in a complete path in a circuit is zero. The electric potential in a complete path in a circuit remains constant.

A series circuit has only one complete path, so the loads must share the amount of electric potential. The total electric potential across the loads must add up to the electric potential at the source (or sources). If V_{series} is the electric potential difference across the source of electrical energy, and the subscripts identify the loads, then

$$V_{\text{series}} = V_1 + V_2 + V_3 + \cdots$$

A parallel circuit has more than one complete path, so the electric potential decrease across each load must be the same as the electric potential increase at the source (or sources). Thus, the electric potential difference across the loads and source must be the same. If V_{parallel} is the electric potential difference across the source of electrical energy, and the subscripts identify the loads, then

$$V_{\text{parallel}} = V_1 = V_2 = V_3 = \cdots$$

Kirchhoff's Current Law

Junctions are points at which you can travel in more than one direction. In electric circuits, junctions are points where the current can split to follow more than one path. **Kirchhoff's current law (KCL)** is stated as follows:

Kirchhoff's current law (KCL) in a closed circuit, the amount of current entering a junction is equal to the amount of current exiting a junction

Kirchhoff's Current Law

In a closed circuit, the amount of current entering a junction is equal to the amount of current exiting a junction.

A series circuit has only one path, so there can be only one possible current. If I_{series} is the current going through the source of electrical energy, and the subscripts identify the loads, then

$$I_{\text{series}} = I_1 = I_2 = I_3 = \cdots$$

LEARNING **TIP**

Remembering KVL and KCL
For a series circuit, voltages add up and currents remain constant. For a parallel circuit, voltages remain constant and currents add up.

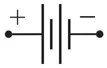
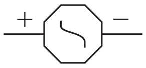
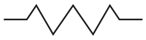
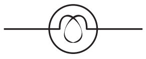
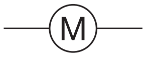
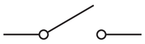
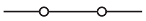
A parallel circuit has more than one complete path, so the current can split, depending on the number of paths. The more complete paths there are, the more ways the current can be divided among the paths. If I_{parallel} represents the current going through the source of electrical energy, and the subscripts identify the loads, then

$$I_{\text{parallel}} = I_1 + I_2 + I_3 + \cdots$$

Applying Kirchhoff's Laws

It is critical to understand the properties of circuits so that they operate as intended. Whether controlling a power plant or designing a circuit, we can use Kirchhoff's laws to analyze circuits to find unknown voltages and currents. To review circuit diagram symbols, see **Table 1**.

Table 1 Circuit Symbols

Part of circuit	Circuit symbol
battery	
variable DC power supply	
connecting wire	
resistor	
lamp	
motor	
open switch closed switch	 

Series Circuits

Assume that the loads are all identical. If three identical light bulbs are connected in series (**Figure 2**), the voltage is divided equally among the three light bulbs. For example, if a 6.0 V battery is connected to three identical light bulbs in series, each light bulb has a voltage of 2.0 V:

$$V_{\text{series}} = V_1 + V_2 + V_3$$

or

$$6.0\text{ V} = 2.0\text{ V} + 2.0\text{ V} + 2.0\text{ V}$$

The amount of current going into a junction is equal to the amount of current going out of the junction. There is no junction in a series circuit; there is only one complete path. So if the battery has a current of 0.20 A, all the loads also have a current of 0.20 A.

Parallel Circuits

Again assume that the loads are all identical. When three identical light bulbs are connected in parallel (**Figure 3**), then the voltage is the same for all three light bulbs. For example, if a 6.0 V battery is connected to three light bulbs in parallel, each light bulb has a voltage of 6.0 V.

The amount of current going into a junction is equal to the amount of current going out of the junction. The three light bulbs connected in parallel are in three independent paths. If the battery has 0.30 A of current, the current is divided equally along each of the three paths to each light bulb:

$$I_{\text{parallel}} = I_1 + I_2 + I_3$$

or

$$0.30\text{ A} = 0.10\text{ A} + 0.10\text{ A} + 0.10\text{ A}$$

In the following Tutorial, you will learn how to solve problems involving mixed circuits that contain both series and parallel connections.

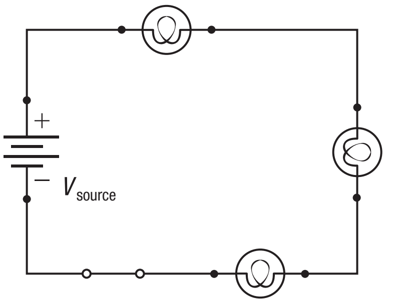


Figure 2 Series circuit

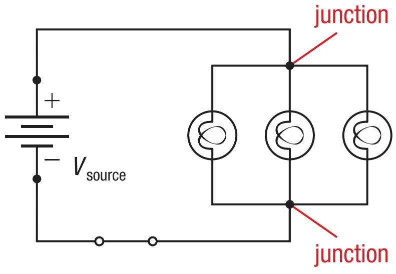


Figure 3 Parallel circuit

Tutorial 1 Applying Kirchhoff's Laws

Although we sometimes assume that all the loads in a circuit are identical, in the real world this is usually not the case. Circuits are rarely all series or all parallel; they have a mixture of connections. The following Tutorial shows you how to analyze mixed circuits with various loads.

CASE 1: APPLYING KIRCHHOFF'S VOLTAGE LAW TO A MIXED CIRCUIT

To analyze a mixed circuit, start by separating the circuit into sections that are connected in parallel and sections that are connected in series. Consider the circuit in **Figure 4** and note the parts labelled "series connection" and "parallel connection." **Figure 5** shows how to view the circuit as two complete paths. Suppose the voltages at the source, lamp 1, and lamp 3 are 40 V, 10 V, and 20 V, respectively. Find the voltages at lamp 2 and lamp 4.

Using this approach of two separate paths, you can think of two completely independent series circuits.

Using KVL for a series circuit, you can solve for V_2:

$$\begin{aligned} V_{\text{source}} &= V_1 + V_2 + V_3 \\ 40\text{ V} &= 10\text{ V} + V_2 + 20\text{ V} \\ 40\text{ V} &= 30\text{ V} + V_2 \\ V_2 &= 10\text{ V} \end{aligned}$$

If you apply the same thinking to the other path, you can solve for V_4:

$$\begin{aligned} V_{\text{source}} &= V_1 + V_2 + V_4 \\ 40\text{ V} &= 10\text{ V} + 10\text{ V} + V_4 \\ 40\text{ V} &= 20\text{ V} + V_4 \\ V_4 &= 20\text{ V} \end{aligned}$$

According to KVL, in a parallel circuit, the voltages are the same. Both V_3 and V_4 are equal to 20 V, as expected, because the potential difference across loads in parallel is always equal.

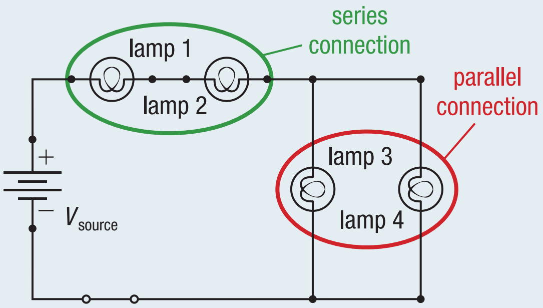


Figure 4 You can look at this circuit as two complete circuits.

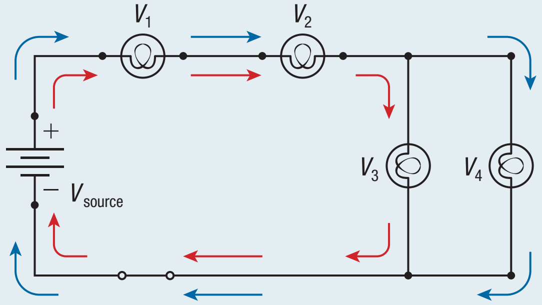


Figure 5 The red path from the source to lamp 1, lamp 2, lamp 3, and back to the source is one path. The blue path from the source to lamp 1, lamp 2, lamp 4, and back to the source is another path.

CASE 2: APPLYING KIRCHHOFF'S CURRENT LAW TO A MIXED CIRCUIT

Using the same circuit, you can use KCL to determine the current. The current in a series circuit is constant and the same as the source current. The current in a parallel circuit is divided along the paths. Suppose you are given the following information: $I_{\text{source}} = 0.40$ A and $I_3 = 0.10$ A. Using these values and KCL, you can find I_1 and I_2.

$$\begin{aligned} I_{\text{series}} &= I_1 = I_2 \\ 0.40\text{ A} &= I_1 = I_2 \end{aligned}$$

Therefore, $I_1 = 0.40$ A and $I_2 = 0.40$ A.

The amount of current entering a junction is equal to the amount of current exiting the junction. You can write this as

$$\begin{aligned} I_{\text{parallel}} &= I_3 + I_4 \\ 0.40\text{ A} &= 0.10\text{ A} + I_4 \\ I_4 &= 0.30\text{ A} \end{aligned}$$

So I_4 is equal to 0.30 A (**Figure 6**).

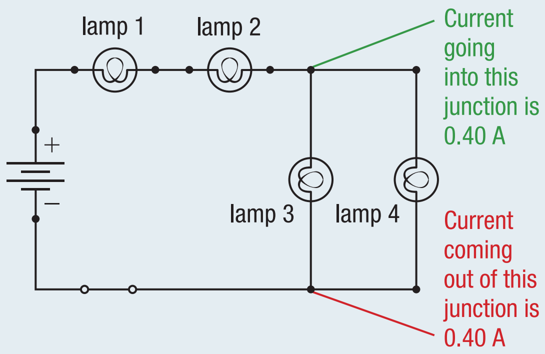

lamp 1
lamp 2
Current going into this junction is 0.40 A
+
−
lamp 3
lamp 4
Current coming out of this junction is 0.40 A

Figure 6 The current entering a junction equals the current exiting the junction.

Practice

1. For the circuit in **Figure 7**, $V_{\text{source}} = 60.0$ V, $V_1 = 20.0$ V, and $V_3 = 15$ V. Determine V_2, V_4, and V_5. T/I [ans: $V_2 = 25$ V; $V_4 = 15$ V; $V_5 = 15$ V]
2. For the circuit in Figure 7, $I_1 = 0.70$ A, $I_3 = 0.10$ A, and $I_5 = 0.20$ A. Determine I_{source}, I_2, and I_4. T/I [ans: $I_{\text{source}} = 0.70$ A; $I_2 = 0.70$ A; $I_4 = 0.40$ A]

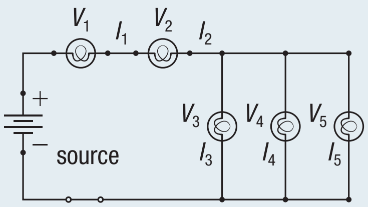


Figure 7

11.6 Summary

- Kirchhoff's voltage law (KVL) states that the voltage gains are equal to the voltage drops in a complete path in a circuit.
- Kirchhoff's current law (KCL) states that the current entering a junction is equal to the current exiting a junction in a circuit.
- The equations for Kirchhoff's laws are

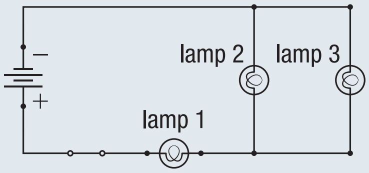
$$V_{\text{series}} = V_1 + V_2 + V_3 + \cdots \qquad V_{\text{parallel}} = V_1 = V_2 = V_3 = \cdots$$

$$I_{\text{series}} = I_1 = I_2 = I_3 = \cdots \qquad I_{\text{parallel}} = I_1 + I_2 + I_3 + \cdots$$

11.6 Questions

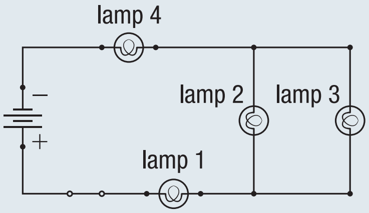
1. What is wrong with the following information? State whether you are applying KCL or KVL in your answer. K/U C
    (a) The current going into a parallel circuit is listed as 0.50 A and the current coming out of the parallel circuit is listed as 0.30 A.
    (b) A student measures the voltage across each of the three loads in a series circuit to be 10 V each. The voltage across the source is measured to be 10 V.
    (c) For a circuit with two lamps connected in parallel, a student measures the voltage drop across one lamp to be 20 V. The student measures the voltage drop across the second lamp to be 10 V.
    (d) A student is using an ammeter and notes that it reads 0.15 A on the first lamp, 0.20 A on the second lamp, and 0.25 A on the third lamp. The student says the lamps are connected in series.
2. For each of the following circuits, the given values are listed in a table. Copy each table into your notebook and find the missing values. T/I C

(a)



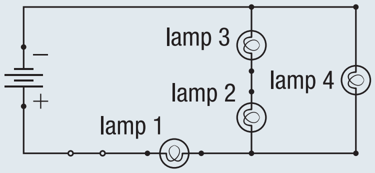
Item	*V* (V)	*I* (A)
source		
lamp 1	2.0	3.0
lamp 2	1.0	1.5
lamp 3		

(b)



Item	*V* (V)	*I* (A)
source	24.0	2.0
lamp 1	10.0	
lamp 2	6.0	1.0
lamp 3		
lamp 4		

(c)

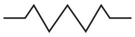


Item	*V* (V)	*I* (A)
source	6.0	4.0
lamp 1		
lamp 2	1.0	2.0
lamp 3	2.0	
lamp 4		

Electrical Resistance

11.7

If you ride your bike down a smooth road and then through some mud, you would immediately notice that it is difficult to maintain the same speed. You would experience a resistance to your movement. In a similar way, all matter has some resistance to the flow of electric current. **Electrical resistance (*R*)** is a measure of how difficult it is for electric current to travel through a material. Some materials have a high resistance—they do not allow electrical currents through easily. Insulators such as plastics and rubber have high resistance. Other materials have a low resistance—they allow electrical currents through more easily. Metals have low resistance and are good conductors of electric current.

Resistors are electrical devices that have a specific resistance. In an electric circuit, you can use a high resistance or a low resistance, depending on the desired effect. For example, for a speaker wire you would use a resistor with a low resistance because you want a large current to reach the speaker to produce loud sounds. If you want a low current in a circuit so that the fine wires are not damaged, it makes more sense to use a resistor with a high resistance. When more power is required, resistors are typically wire wound (a wire is wound several times to reach the desired resistance value). Since these resistors handle a lot of power, they will heat up, so the wire is encased in a ceramic material. Resistors can also be variable. Their resistance can be changed by typically using a dial. These types of resistors are called rheostats. The symbol for a resistor is .

electrical resistance (*R*) a property of matter that describes how difficult it is for electric current to travel through a material

resistor an electrical device that has a specific resistance value

Mini **Investigation**

Determining Unknown Resistance

Skills: Performing, Observing, Analyzing

SKILLS HANDBOOK **A2.1, A2.2, A6.5**

In this investigation, your teacher will provide you with a resistor of unknown value and you will determine its resistance.

Equipment and Materials: variable DC power supply; ceramic resistors of different values for each group; 5–6 alligator clip leads; voltmeter; ammeter

1. Be sure that the power supply is off, and then connect the circuit as shown in **Figure 1**. Have your teacher check the circuit.

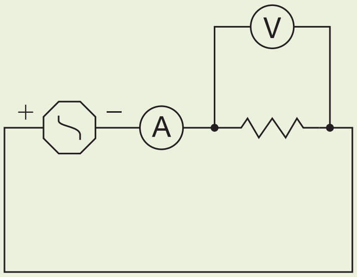


Figure 1 Circuit diagram

2. Turn the power supply to its lowest setting, and then turn it on.
3. Turn the power supply voltage up slowly until there is a reading on the ammeter. Record the voltage in volts and the current in amperes.
4. Increase the voltage slightly until you notice a change in the current. Record the voltage and current again. Repeat until you have five measurements of voltage and five measurements of current. Once you have completed your measurements, turn off the power supply and let the resistor cool.

Always make sure that the power supply is off before connecting your circuit. Always have your teacher check the circuit before turning on the power supply, and turn it up slowly. Do not touch the resistor, it may become very hot.

A. Plot a graph with voltage on the *y*-axis and current on the *x*-axis. Include a line of best fit and calculate the slope. T/I C

B. Take your calculated slope to your teacher and compare values from your graph to the resistance of the resistor. What is the percentage difference? T/I

C. Look at another student's graph for a different resistor. What do you notice? T/I

Ohm's Law

When you perform a scientific investigation on the properties of a material, you are trying to learn something new about the material. You do a controlled investigation to observe a cause-and-effect relationship between two variables while keeping all other conditions constant.

In the Mini Investigation on the previous page, the two variables that you investigated were the voltage applied to the resistor and the electric current going through the resistor. As the amount of voltage increased, the amount of electric current also increased. If you repeated the investigation with a completely different resistor (with all other conditions being the same), you would observe different values for voltage and current, but the resulting relationship is the same—when the voltage increases, the current increases. Georg Simon Ohm did similar investigations, and his results revealed the property of electrical resistance. The unit of resistance is called the ohm (Ω) in honour of Ohm's contributions to our understanding of electrical resistance. **Ohm's law** is stated as follows:

Ohm's law the potential difference between any two points in a conductor varies directly with the current between two points if the temperature remains constant

Ohm's Law

The voltage in a conductor is proportional to the current if the temperature remains constant. So $V \propto I$.

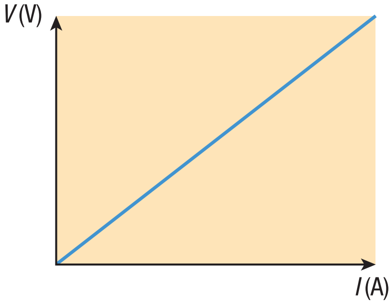


Figure 2 Graph of applied voltage against current. Note that the graph has a constant slope.

A graph of voltage against current is a straight line (**Figure 2**). The slope of the graph is constant, and this constant is the electrical resistance, R:

$$V \propto I$$

Therefore,

$$V = \text{constant} \times I$$

$$\text{constant} = \frac{V}{I}$$

$$R = \frac{V}{I}$$

where R = resistance measured in volts per ampere, or ohms (Ω), V = electric potential difference or voltage measured in volts (V), and I = electric current measured in amperes (A). In the following Tutorial, you will use Ohm's law to calculate an unknown resistance.

LEARNING **TIP**

Remembering Ohm's Law

The equation for Ohm's law can be rewritten as $V = IR$, which is easier to remember if you use a mnemonic: VIR = Very Important Resistance.

Tutorial 1 Using Ohm's Law

Ohm's law can be used to determine an unknown resistance in a circuit. In the following Sample Problem, we will use the voltage and current to solve for the resistance of a load.

Sample Problem 1

Calculate the resistance of a load with a voltage of 25 V and a current of 410 mA.

Given: $V = 25$ V; $I = 410$ mA

Required: R

Analysis: $R = \frac{V}{I}$

Solution: Convert the current to amperes to get the answer in ohms:

$$I = 410\ \cancel{\text{mA}} \times \frac{1\ \text{A}}{1000\ \cancel{\text{mA}}}$$

$$I = 0.41\ \text{A}$$

$$R = \frac{V}{I}$$

$$= \frac{25\text{ V}}{0.41\text{ A}}$$

$$R = 61\ \Omega$$

Statement: The resistance is 61 Ω.

Practice

1. What is the resistance of a toaster element with a voltage of 120 V and a current of 6.5 A? T/I [ans: 18 Ω]
2. What is the resistance of a car starter with 450 A of current and a voltage of 12 V? T/I [ans: 0.027 Ω]

Consequences of Resistance

All of the electrical components in a circuit have electrical resistance. The connecting wires and control devices, such as switches, typically have small resistances. If you touch an insulated alligator clip lead while performing an investigation, you will notice that the lead has become warmer. This is because of its resistance; some of the electrical energy is being converted into thermal energy. Some loads depend on this conversion to function, such as incandescent light bulbs. The bulb converts electrical energy into thermal energy and light energy, because of the electrical resistance of its tiny wire filament. Even batteries can get warm if operated continuously, because they have an internal resistance.

When electrical energy from a power plant travels through conducting wires to reach your home, some electrical energy is transformed into thermal energy because of the resistance of the wires. This thermal energy is wasted; it is not being used by any electrical device. This decreases the efficiency of the transfer of energy. The wires need to be manufactured from a material with low resistance.

Superconductors are special materials that have no electrical resistance. There is a lot of interest in these because of the potential to eliminate the thermal energy wasted in wires. Initially, superconductivity was only observed in liquid helium at –269 °C. It would not be practical to make a conductor out of helium, and it is extremely difficult to reach such a low temperature. Research has steadily moved the temperature upward. Currently, superconductivity has been demonstrated in a special material nicknamed Hg-1223 (actually $HgBa_2Ca_2Cu_3O_8$) at –135 °C. The goal is to be able to make circuits from superconducting material at room temperature. Imagine a computer that does not need cooling, or power plant transmission wires that are 100 % efficient.

Even though superconductivity requires very low temperatures, it is still being actively used in technologies around the world. One example is the magnetic resonance imaging (MRI) device, which you will learn about in Section 12.7. The MRI uses superconductors to create a very strong magnet. Superconductors are also used in particle accelerators like the Large Hadron Collider.

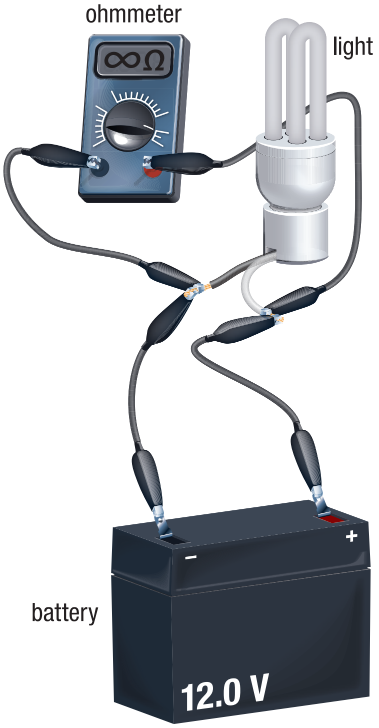


Figure 3 The load in this circuit is not functioning. The display on the ohmmeter shows that the reading is off the scale of the device. Note that the circuit must be switched off before measurements are made with an ohmmeter.

Measuring Resistance

ohmmeter a device that measures electrical resistance

An **ohmmeter** is a device used to measure electrical resistance. Ohmmeters are connected in parallel and must never be used on a circuit if the circuit is live. Always turn the power off before using an ohmmeter. The symbol for an ohmmeter is —(Ω)— .

An ohmmeter is useful for testing whether a load works. Typically, loads have low resistance. When you test a load with an ohmmeter, the resistance should read low. If the resistance reads off the scale, the load likely has a bad connection and will not work (**Figure 3**).

11.7 Summary

- Electrical resistance is a property of all matter that describes how difficult it is for an electric current to travel through the matter.
- Resistors are devices with specific electrical resistance.
- Ohm's law states that the voltage in a conductor is proportional to the current if the temperature remains constant.
- Ohm's law can be stated as an equation: $R = \frac{V}{I}$.
- All electrical components have an electrical resistance.
- Resistance in a wire will cause some of the electrical energy flowing through the wire to be converted into thermal energy. This thermal energy is often wasted.
- Superconductors are special materials with no electrical resistance.
- An ohmmeter is a device used to measure electrical resistance and should be connected in parallel to a circuit that is switched off.
- The symbol for an ohmmeter is —(Ω)— .

11.7 Questions

1. Rearrange the equation for resistance to solve for (a) current and (b) voltage. K/U
2. A portable electric fan is operating on a 9.0 V battery. The current going into the motor is 160 mA. Determine the resistance of the portable fan. T/I
3. Dry human skin has a resistance of approximately 100 000 Ω. If a person were accidentally to touch the terminals of a 9.0 V battery, what would be the current going through the skin? T/I
4. Wet human skin has a resistance of approximately 1000 Ω. If a person were accidentally to touch a live circuit with 120 V of electric potential difference, what would be the current going through the skin? T/I
5. A home theatre system has a speaker with a resistance of 8.0 Ω. It is connected to an amplifier that has a voltage of 5.2 V. Determine the current going to the speaker. T/I
6. A laptop computer charger has a current of 2.07 A. The resistance of the charger is 8.05 Ω. Determine the voltage of the charger. T/I
7. Describe electrical resistance in your own words. K/U C
8. Graph the data in **Table 1** and determine the resistance. K/U T/I

Table 1

Voltage (V)	Current (mA)
12	151
15	188
18	226
21	261

9. Which line on the graph in **Figure 4** represents the higher value of resistance? Explain. K/U C

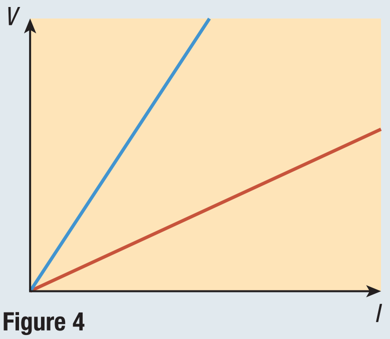


Figure 4

10. A student connects an ohmmeter in series to an operating circuit. What two things has the student done incorrectly? K/U
11. Describe and explain a situation where electrical resistance is desirable and a situation where it is undesirable. C A
12. Find the missing values in **Table 2** below. Take care with units. T/I

Table 2

Current	Voltage (V)	Resistance (Ω)
25 mA	12	
1.2 A		510
375 μA	0.25	
(answer in A)	120	33
(answer in mA)	1.5	1500

Resistors in Circuits

11.8

You have just bought a ticket for an amusement park. There is a lineup and you do not want to waste time—you want to get on the rides. Unfortunately, there is only one turnstile open. In this case, there is a lot of resistance to the flow of people into the park. You can think of the turnstiles as resistors and the flow of people into the park as electric current.

Connecting Resistors in Series

Imagine adding another turnstile in front of the one you just passed through. Now everyone needs to pass through two turnstiles, one after the other. This slows down the flow of people into the park, which means that there is more resistance to the overall flow. The situation in an electric circuit is similar. Adding more resistors to a series circuit decreases the current in the circuit. The decreased current is a result of the increased resistance.

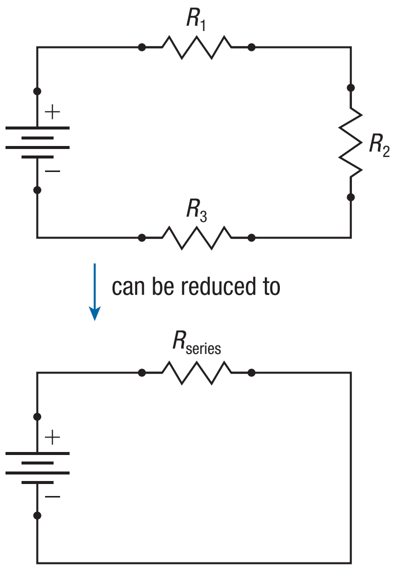


Figure 1 Three resistors connected in series can be reduced to a single resistor with an equivalent value of R_{series}.

equivalent resistance the total resistance of a group of resistors connected in series or parallel

To find out how much the current is affected by increasing the resistance, consider the circuit shown in **Figure 1**. In this circuit, the three resistors can be reduced to a single resistor with a resistance equivalent to the total resistance of the three resistors. **Equivalent resistance** is the total resistance of a group of resistors in a circuit. You can use Kirchhoff's laws and Ohm's law to derive the equivalent resistance for resistors in a series circuit. Start with KVL for a series circuit:

$$V_{\text{series}} = V_1 + V_2 + V_3$$

Substitute Ohm's Law in the form $V = IR$:

$$I_{\text{series}}R_{\text{series}} = I_1R_1 + I_2R_2 + I_3R_3$$

In a series circuit, the current is constant and the same at all points (KCL). So the currents on the left side will cancel with the currents on the right side:

$$\begin{aligned} I_{\text{series}}R_{\text{series}} &= I_1R_1 + I_2R_2 + I_3R_3 \\ \cancel{I_{\text{series}}}R_{\text{series}} &= \cancel{I_{\text{series}}}R_1 + \cancel{I_{\text{series}}}R_2 + \cancel{I_{\text{series}}}R_3 \\ R_{\text{series}} &= R_1 + R_2 + R_3 \end{aligned}$$

Therefore, in a series circuit the equivalent resistance is given by

$$R_{\text{series}} = R_1 + R_2 + R_3 + \cdots$$

So the three resistors can be reduced to a single resistor with a value equivalent to the sum of the three resistances. In the following Tutorial, you will apply the equivalent resistance equation to solve for missing values in a series circuit.

Tutorial 1 Equivalent Resistance in a Series Circuit

Sample Problem 1

Four resistors are connected in series in a circuit. The resistances are as follows: $R_1 = 41\ \Omega$, $R_2 = 51.75\ \Omega$, $R_3 = 11.1\ \Omega$, and $R_4 = 102.008\ \Omega$. Calculate the equivalent resistance.

Given: $R_1 = 41\ \Omega$; $R_2 = 51.75\ \Omega$; $R_3 = 11.1\ \Omega$; $R_4 = 102.008\ \Omega$

Required: R_{series}

Analysis: $R_{\text{series}} = R_1 + R_2 + R_3 + R_4$

Solution:
$$\begin{aligned} R_{\text{series}} &= R_1 + R_2 + R_3 + R_4 \\ &= 41\ \Omega + 51.75\ \Omega + 11.1\ \Omega + 102.008\ \Omega \\ R_{\text{series}} &= 206\ \Omega \end{aligned}$$

Statement: The equivalent resistance is 206 Ω.

Practice

1. What is the equivalent resistance for a 25.2 Ω resistor connected in series with a 28.12 Ω resistor? T/I [ans: 53.3 Ω]
2. What is the equivalent resistance for three 53.0 Ω resistors connected in series? T/I [ans: 159 Ω]

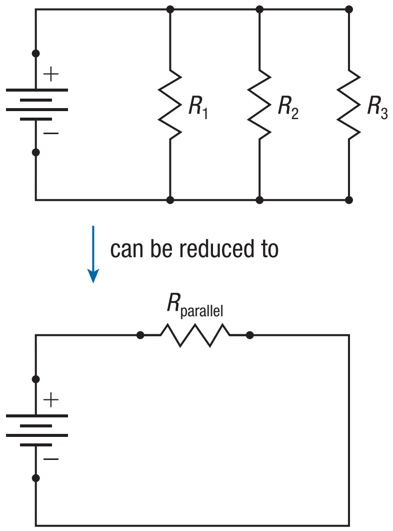


Figure 2 Three resistors connected in parallel can be reduced to a single resistor with an equivalent value of R_{parallel}.

Connecting Resistors in Parallel

Think about the amusement park turnstiles again. If enough turnstiles were open, each person could have their own turnstile to go through. This would greatly increase the flow of people into the park. If the flow of people into the park has increased, there must be a decrease in the resistance to overall flow. Even though each individual has experienced resistance in going through one turnstile, the overall flow of people into the amusement park has increased. A similar situation occurs when resistors are connected in parallel. The more resistors you connect in parallel, the greater the current. Therefore, the total resistance must decrease.

To understand why this occurs, consider the increase in the number of pathways when you connect resistors in parallel. With each additional parallel connection, you increase the number of pathways for the electric current. If there are more pathways, you would expect more electric current.

You can derive an equivalent resistance equation for resistors in a parallel circuit. Start with KCL for the parallel circuit shown in **Figure 2:**

$$I_{\text{parallel}} = I_1 + I_2 + I_3$$

Substitute Ohm's law in the form $I = \frac{V}{R}$:

$$\frac{V_{\text{parallel}}}{R_{\text{parallel}}} = \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}$$

In a parallel circuit, the voltage is constant and the same at all points. Using KVL, the voltages on the left side will cancel with the voltages on the right side:

$$\frac{V_{\text{parallel}}}{R_{\text{parallel}}} = \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}$$

$$\frac{\cancel{V_{\text{parallel}}}}{R_{\text{parallel}}} = \frac{\cancel{V_{\text{parallel}}}}{R_1} + \frac{\cancel{V_{\text{parallel}}}}{R_2} + \frac{\cancel{V_{\text{parallel}}}}{R_3}$$

$$\frac{1}{R_{\text{parallel}}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

Therefore, in a parallel circuit the equivalent resistance is given by

$$\frac{1}{R_{\text{parallel}}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots$$

LEARNING **TIP**

Equivalent Resistance in a Parallel Circuit

For a parallel circuit, the equivalent resistance is always less than the least resistance in the circuit.

Tutorial **2** Equivalent Resistance in a Parallel Circuit

Sample Problem 1

Three resistors are connected in parallel in a circuit. The resistances are $R_1 = 15\ \Omega$, $R_2 = 12\ \Omega$, and $R_3 = 10\ \Omega$. Calculate the equivalent resistance.

Given: $R_1 = 15\ \Omega$; $R_2 = 12\ \Omega$; $R_3 = 10\ \Omega$

Required: R_{parallel}

Analysis: $\frac{1}{R_{\text{parallel}}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$

Solution:

$$\frac{1}{R_{\text{parallel}}} = \frac{1}{15\ \Omega} + \frac{1}{12\ \Omega} + \frac{1}{10\ \Omega}$$

$$\frac{1}{R_{\text{parallel}}} = \frac{4}{60\ \Omega} + \frac{5}{60\ \Omega} + \frac{6}{60\ \Omega}$$

Find a common denominator.

$$\frac{1}{R_{\text{parallel}}} = \frac{15}{60\ \Omega}$$

$$R_{\text{parallel}} = \frac{60\ \Omega}{15}$$

$$R_{\text{parallel}} = 4\ \Omega$$

Find the reciprocal to solve for R_{parallel}.

Statement: The equivalent resistance is 4 Ω.

Practice

1. What is the equivalent resistance of a 120 Ω resistor connected in parallel with a 60 Ω resistor? T/I [ans: 40 Ω]
2. What is the equivalent resistance of four 20 Ω resistors connected in parallel? T/I [ans: 5 Ω]

Mixed circuits contain both series and parallel connections. As you learned in Section 11.6, to analyze a mixed circuit, you can divide the circuit into sections that are connected in parallel and sections that are connected in series. In the following Tutorial, you will use this strategy to find the equivalent resistance in a circuit with both series and parallel connections.

Tutorial 3 Equivalent Resistance in a Mixed Circuit

Mixed circuits contain both series and parallel connections. To determine the equivalent resistance, work on each part of the circuit separately.

Sample Problem 1

Calculate the equivalent resistance for the circuit shown in **Figure 3**.

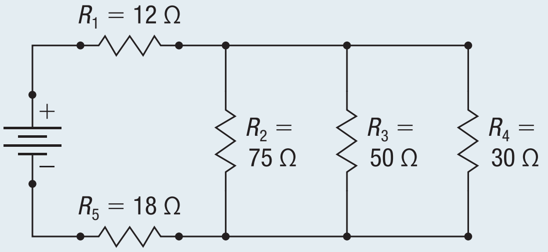
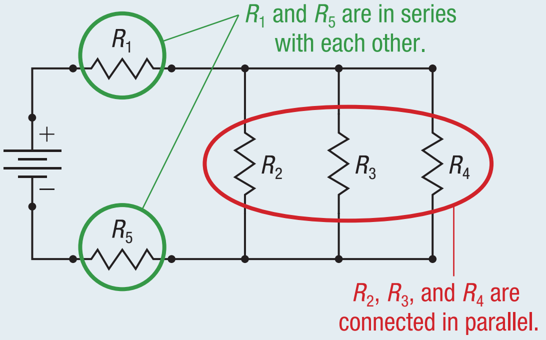


Figure 3

Step 1. Divide the circuit into series and parallel parts, as shown in **Figure 4**.



R_1 and R_5 are in series with each other.

R_2, R_3, and R_4 are connected in parallel.

Figure 4

Step 2. Find the equivalent resistance of the parallel part of the circuit.

$$\frac{1}{R_{\text{parallel}}} = \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}$$

$$\frac{1}{R_{\text{parallel}}} = \frac{1}{75\ \Omega} + \frac{1}{50\ \Omega} + \frac{1}{30\ \Omega}$$

$$\frac{1}{R_{\text{parallel}}} = \frac{2}{150\ \Omega} + \frac{3}{150\ \Omega} + \frac{5}{150\ \Omega}$$

$$\frac{1}{R_{\text{parallel}}} = \frac{10}{150\ \Omega}$$

$$R_{\text{parallel}} = \frac{150\ \Omega}{10}$$

$$R_{\text{parallel}} = 15\ \Omega$$

Step 3. Redraw the circuit using the equivalent resistance from Step 2 (**Figure 5**).

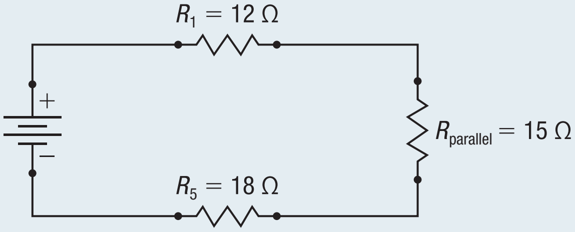


Figure 5

Step 4. Solve to determine the equivalent resistance of the remaining series circuit. Let the equivalent resistance for the complete circuit be R_{total}:

$$\begin{aligned} R_{\text{total}} &= R_1 + R_{\text{parallel}} + R_5 \\ &= 12\ \Omega + 15\ \Omega + 18\ \Omega \\ R_{\text{total}} &= 45\ \Omega \end{aligned}$$

Statement: The equivalent resistance is 45 Ω.

Practice

1. What is the total resistance of the mixed circuits shown in **Figure 6**? Note that each resistor has resistance 5.0 Ω. T/I [ans: (a) 17.5 Ω; (b) 6.3 Ω]

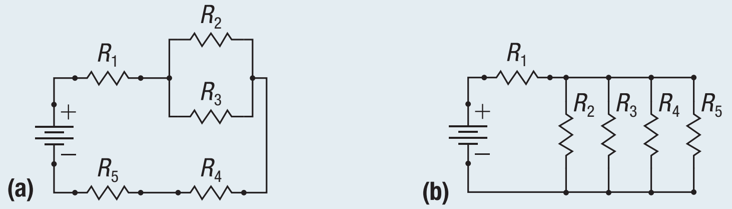


Figure 6

Investigation 11.8.1

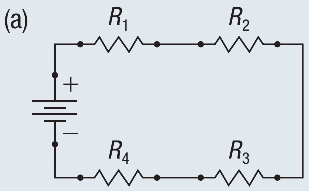
Analyzing Circuits (p. 536)
You have learned about current, electric potential difference, and resistance. You have also learned about Kirchhoff's laws and how they describe how voltage and current are related in series, parallel, and mixed circuits. This Observational Study will give you an opportunity to confirm these laws through the measurement of the three electrical quantities.

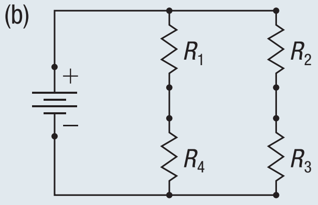
11.8 Summary

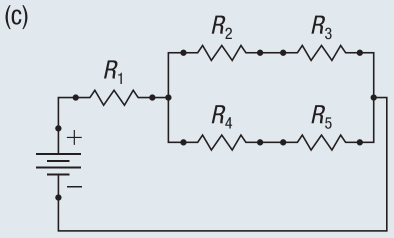
- Connecting resistors in series causes an increase in the total resistance and a decrease in the current.
- A group of resistors connected in series can be reduced to a single equivalent resistor with resistance $R_{\text{series}} = R_1 + R_2 + R_3 + \cdots$.
- Connecting resistors in parallel causes a decrease in the total resistance and an increase in current.
- A group of resistors connected in parallel can be reduced to a single equivalent resistor with resistance $\frac{1}{R_{\text{parallel}}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots$.

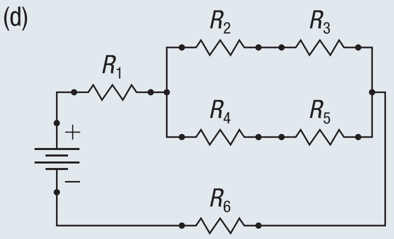
11.8 Questions

1. Using $R_{\text{series}} = R_1 + R_2 + R_3 + \cdots$ and Ohm's law, derive Kirchhoff's voltage law for a series circuit. T/I
2. Using $\frac{1}{R_{\text{parallel}}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots$ and Ohm's law, derive Kirchhoff's current law for a parallel circuit. T/I
3. Prove that the equivalent resistance of two identical resistors in parallel is equal to half the resistance of one of the resistors. T/I
4. Recall that all loads have electrical resistance. Suppose that you connect a number of loads in your home in parallel. What will happen to the amount of electric current with each load that you add? Would you be concerned about this? Explain your answer. K/U C
5. What is the equivalent resistance of the following circuits? Each resistor has resistance 12.0 Ω. K/U T/I









Circuit Analysis

11.9

Circuit analysis is a method of solving problems related to electric circuits which combines Ohm's law, Kirchhoff's laws, and the problem-solving techniques you learned for finding equivalent resistance. The Tutorials in this section will provide possible methods for solving circuit problems. There is always more than one way to solve a circuit problem, but the method you choose must follow the circuit laws.

Tutorial 1 Circuit Analysis for a Mixed Circuit

There are two general types of circuit analysis problems. In the first type, you are given only the resistance values and a source voltage. In the second type, you are given a mix of current, voltage, and resistance values. The following Sample Problems will take you through both types of problem. (Hint: When you get to a point where you have solved for two of the three variables, use Ohm's law.)

CASE 1: RESISTANCE VALUES ARE GIVEN

In this type of circuit analysis problem, you are given only the resistance values and a source voltage.

Sample Problem 1

The circuit shown in **Figure 1** has a source voltage of 12.0 V and resistance values of $R_1 = 15.0\ \Omega$, $R_2 = 25.0\ \Omega$, and $R_3 = 35.0\ \Omega$. Find values for I_{source}, I_1, I_2, I_3, V_1, V_2, V_3, and R_{total}.

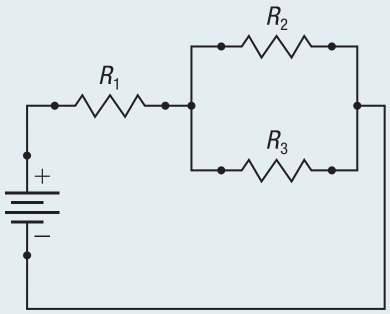
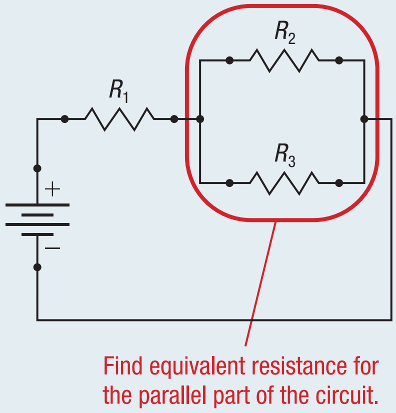


Figure 1

Step 1. Find the total resistance of the circuit. Start by finding the equivalent resistance for the parallel part of the circuit (**Figure 2**).



R_2
R_1
R_3
+
−
Find equivalent resistance for the parallel part of the circuit.

Figure 2

$$\frac{1}{R_{\text{parallel}}} = \frac{1}{R_2} + \frac{1}{R_3}$$

$$\frac{1}{R_{\text{parallel}}} = \frac{1}{25.0\ \Omega} + \frac{1}{35.0\ \Omega}$$

$$R_{\text{parallel}} = 14.583\ \Omega \text{ (two extra digits carried)}$$

Now find the total resistance.

R_{parallel} is in series with R_1, so

$$\begin{aligned} R_{\text{total}} &= R_1 + R_{\text{parallel}} \\ &= 15.0\ \Omega + 14.583\ \Omega \\ R_{\text{total}} &= 29.583\ \Omega \text{ (two extra digits carried)} \end{aligned}$$

Step 2. Find I_{source} using Ohm's law written as $I = \frac{V}{R}$.

$$\begin{aligned} I_{\text{source}} &= \frac{V_{\text{source}}}{R_{\text{total}}} \\ &= \frac{12.0\ \text{V}}{29.583\ \Omega} \\ I_{\text{source}} &= 0.4056\ \text{A} \end{aligned}$$

Step 3. Apply KCL to find I_1. Note that the source is in series with I_1 and the parallel part I_{parallel}.

$$I_{\text{series}} = I_1 = I_2 = I_3 = \cdots$$

$I_{\text{series}} = I_{\text{source}} = I_1 = I_{\text{parallel}} = 0.4056$ A (two extra digits carried)

Step 4. Find V_1 using Ohm's law written as $V = IR$.

$$\begin{aligned} V_1 &= I_1 R_1 \\ &= (0.4056\ \text{A})(15.0\ \Omega) \\ V_1 &= 6.084\ \text{V (two extra digits carried)} \end{aligned}$$

Step 5. Apply KVL to find V_{parallel}.

$$\begin{aligned} V_{\text{series}} &= V_1 + V_2 + V_3 + \cdots \\ V_{\text{source}} &= V_1 + V_{\text{parallel}} \\ V_{\text{parallel}} &= V_{\text{source}} - V_1 \\ V_{\text{parallel}} &= 12.0\text{ V} - 6.084\text{ V} \\ V_{\text{parallel}} &= 5.916\text{ V} \end{aligned}$$

Step 6. Apply KVL to find V_2 and V_3.

$$V_{\text{parallel}} = V_1 = V_2 = V_3 = \cdots$$

$$V_{\text{parallel}} = V_2 = V_3 = 5.916\text{ V (two extra digits carried)}$$

Step 7. Find I_2 and I_3 using Ohm's law written as $I = \frac{V}{R}$.

$$\begin{aligned} I_2 &= \frac{V_2}{R_2} \\ &= \frac{5.916\text{ V}}{25.0\ \Omega} \\ I_2 &= 0.2366\text{ A (two extra digits carried)} \end{aligned}$$

$$\begin{aligned} I_3 &= \frac{V_3}{R_3} \\ &= \frac{5.916\text{ V}}{35.0\ \Omega} \\ I_3 &= 0.169\text{ A} \end{aligned}$$

Step 8. Record your final answers using the correct number of significant digits. Look back at the circuit and see if the values you have calculated coincide with Kirchhoff's laws (**Figure 3**).

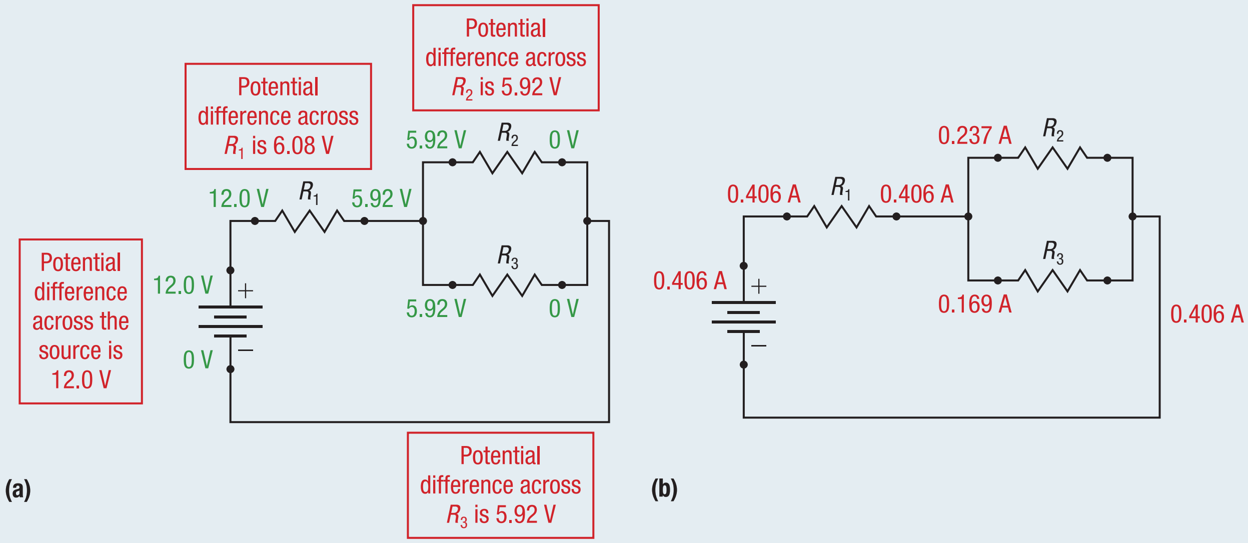

Potential difference across R_1 is 6.08 V
Potential difference across R_2 is 5.92 V
Potential difference across the source is 12.0 V
Potential difference across R_3 is 5.92 V
12.0 V
R_1
5.92 V
5.92 V
R_2
0 V
R_3
5.92 V
0 V
12.0 V
+
−
0 V
(a)
0.237 A
R_2
0.406 A
R_1
0.406 A
R_3
0.406 A
+
−
0.169 A
0.406 A
(b)

Figure 3 (a) The electric potential energies associated with the electrons are represented in green. We chose a reference point of 0 V. The red boxes represent the voltage across each point in the circuit. In each complete path, the sum of the voltage gains (12.0 V) equals the sum of the voltage drops (6.08 V + 5.92 V). Therefore, you have solved the problem correctly.
(b) The red values represent the current at various points in the circuit. The only junction is where the current splits into R_2 and R_3. The current going into the junction is 0.406 A. The current coming out is also 0.406 A. The current in each path of the parallel part of the circuit must add up to 0.406 A. A check of the values (0.237 A + 0.169 A = 0.406 A) shows that the current in the parallel part of the circuit adds up to 0.406 A.

Practice

1. Repeat Sample Problem 1 with the following values: $V_{\text{source}} = 40.0$ V, $R_1 = 25.0\ \Omega$, $R_2 = 30.0\ \Omega$, and $R_3 = 30.0\ \Omega$. T/I
   [ans: $R_{\text{total}} = 40.0\ \Omega$; $I_{\text{source}} = 1.00$ A; $I_1 = 1.00$ A; $I_2 = 0.500$ A; $I_3 = 0.500$ A; $V_1 = 25.0$ V; $V_2 = 15.0$ V; $V_3 = 15.0$ V]

CASE 2: ONLY SOME RESISTANCE VALUES ARE GIVEN

This is the type of circuit analysis problem where you are missing various values. You will use Ohm's law and Kirchhoff's laws to solve this circuit problem.

Sample Problem 2

The circuit shown in **Figure 4** has $V_{\text{source}} = 12.0\text{ V}$, $I_1 = 0.50\text{ A}$, $V_3 = 2.5\text{ V}$, $V_4 = 5.0\text{ V}$, and $R_3 = 10.0\ \Omega$. Find I_{source}, I_2, I_3, I_4, V_1, V_2, R_1, R_2, R_4, and R_{total}.

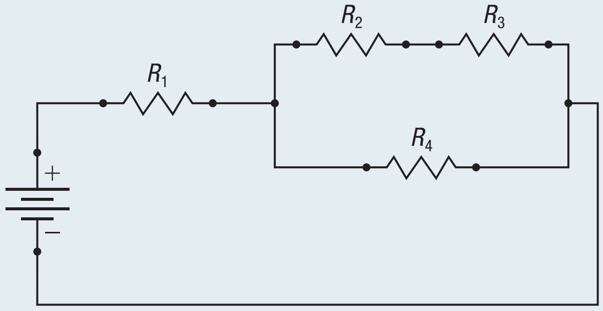


Figure 4

Step 1. Apply KVL to any *complete* pathway. In this case, one complete pathway involves the source, resistor 1, and resistor 4.

$$\begin{aligned} V_{\text{source}} &= V_1 + V_4 \\ V_1 &= V_{\text{source}} - V_4 \\ V_1 &= 12.0\text{ V} - 5.0\text{ V} \\ V_1 &= 7.0\text{ V} \end{aligned}$$

Step 2. Apply KVL to another *complete* pathway. In this case, another complete pathway involves the source, resistor 1, resistor 2, and resistor 3.

$$\begin{aligned} V_{\text{source}} &= V_1 + V_2 + V_3 \\ V_2 &= V_{\text{source}} - V_1 - V_3 \\ V_2 &= 12.0\text{ V} - 7.0\text{ V} - 2.5\text{ V} \\ V_2 &= 2.5\text{ V} \end{aligned}$$

Step 3. Find I_3 using Ohm's law written as $I = \frac{V}{R}$.

$$\begin{aligned} I_3 &= \frac{V_3}{R_3} \\ &= \frac{2.5\text{ V}}{10.0\ \Omega} \\ I_3 &= 0.25\text{ A} \end{aligned}$$

Step 4. Apply KCL to find the missing current values. Note that $I_{2,3}$ represents the current going through the path that contains I_2 and I_3.

Find I_{source}: $$\begin{aligned} I_{\text{source}} &= I_1 \\ &= 0.50\text{ A} \end{aligned}$$

Find I_2: $$\begin{aligned} I_{\text{series}} &= I_2 \\ &= I_3 \\ &= 0.25\text{ A} \\ I_2 &= 0.25\text{ A} \end{aligned}$$

Find I_4: $$\begin{aligned} I_{\text{source}} &= I_{2,3} + I_4 \\ I_4 &= I_{\text{source}} - I_{2,3} \\ I_4 &= 0.50\text{ A} - 0.25\text{ A} \\ I_4 &= 0.25\text{ A} \end{aligned}$$

Step 5. Find all other missing values using Ohm's law.

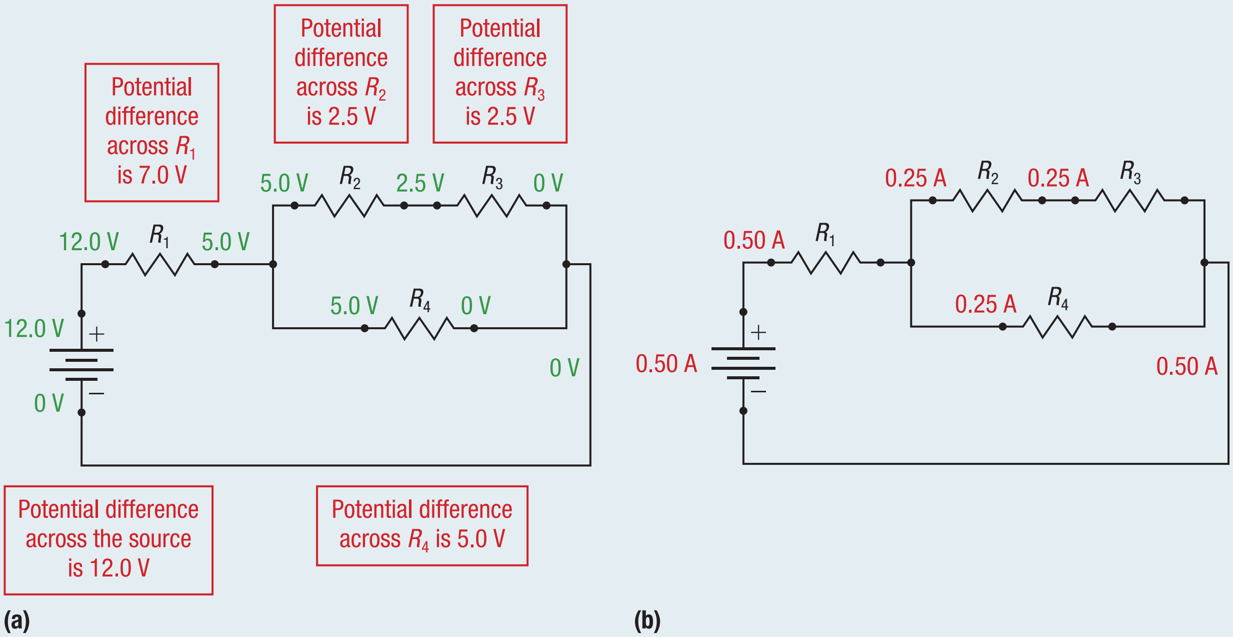
$$\begin{aligned} R_1 &= \frac{V_1}{I_1} \\ &= \frac{7.0\text{ V}}{0.50\text{ A}} \\ R_1 &= 14\ \Omega \end{aligned}$$

$$\begin{aligned} R_2 &= \frac{V_2}{I_2} \\ &= \frac{2.5\text{ V}}{0.25\text{ A}} \\ R_2 &= 10\ \Omega \end{aligned}$$

$$\begin{aligned} R_4 &= \frac{V_4}{I_4} \\ &= \frac{5.0\text{ V}}{0.25\text{ A}} \\ R_4 &= 20\ \Omega \end{aligned}$$

$$\begin{aligned} R_{\text{total}} &= \frac{V_{\text{source}}}{I_{\text{source}}} \\ &= \frac{12.0\text{ V}}{0.50\text{ A}} \\ R_{\text{total}} &= 24\ \Omega \end{aligned}$$

Step 6. Record your final answers with the correct number of significant digits.
Now that you have finished the problem, you can look back at the circuit and see if the values you have calculated coincide with Kirchhoff's laws (**Figure 5**).



Potential difference across R_1 is 7.0 V
Potential difference across R_2 is 2.5 V
Potential difference across R_3 is 2.5 V
5.0 V
R_2
2.5 V
R_3
0 V
12.0 V
R_1
5.0 V
5.0 V
R_4
0 V
12.0 V
+
−
0 V
0 V
Potential difference across the source is 12.0 V
Potential difference across R_4 is 5.0 V
(a)
0.25 A
R_2
0.25 A
R_3
0.50 A
R_1
0.25 A
R_4
+
−
0.50 A
0.50 A
(b)

Figure 5 (a) The electric potential energies associated with the electrons are represented in green. We chose a reference point of 0 V. The red boxes represent the electric potential difference (or voltage) across the electric circuit parts. In one complete path, the sum of the voltage gains (12.0 V) equals the sum of the voltage drops (7.0 V + 2.5 V + 2.5 V). In the other complete path, the sum of the voltage gains (12.0 V) equals the sum of the voltage drops (7.0 V + 5.0 V). Therefore, you have solved the problem correctly.
(b) The red values represent the current at various points in the circuit. The only junction is at the parallel part where the current splits into $R_{2,3}$ (R_2 and R_3 together) and R_4. The current going into the junction is 0.50 A. The current coming out is also 0.50 A. The currents in both paths of the parallel part of the circuit must add up to 0.50 A. A check of the values (0.25 A + 0.25 A = 0.50 A) shows that they do. Note that the current in the two resistors connected in series (R_2 and R_3) stays constant.

Practice

1. Repeat Sample Problem 2 with the following values: $V_{\text{source}} = 42.0$ V, $I_1 = 1.75$ A, $V_2 = 8.75$ V, $V_4 = 17.5$ V, and $R_2 = 35.0\ \Omega$. Find I_{source}, I_2, I_3, I_4, V_1, V_3, R_1, R_3, R_4, and R_{total}. T/I
   [ans: $I_{\text{source}} = 1.75$ A; $I_2 = 0.250$ A; $I_3 = 0.250$ A; $I_4 = 1.50$ A; $V_1 = 24.5$ V; $V_3 = 8.75$ V; $R_1 = 14.0\ \Omega$; $R_3 = 35.0\ \Omega$; $R_4 = 11.7\ \Omega$; $R_{\text{total}} = 24.0\ \Omega$]

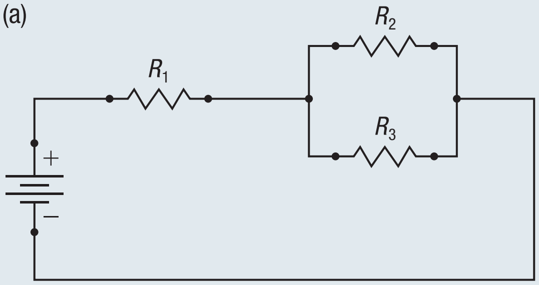
11.9 Summary

- Circuits can be analyzed using a combination of equivalent resistance, Kirchhoff's laws, and Ohm's laws.

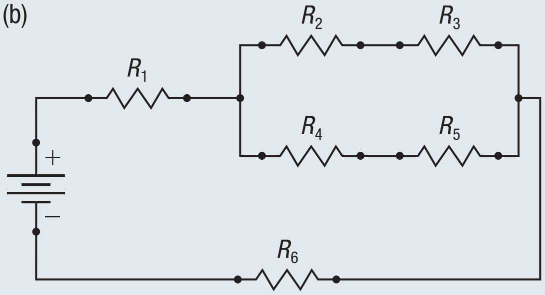
11.9 Questions

1. For each of the circuit diagrams below, the source has a voltage of 6.0 V. Each resistor has resistance 12.0 Ω. Find all the other values of current, voltage, and resistance. T/I

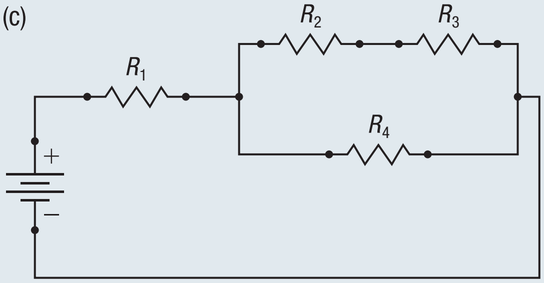
(a)



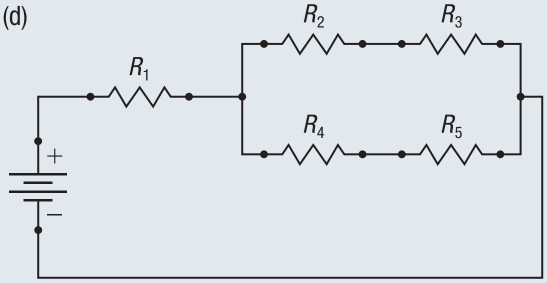
(b)



(c)



(d)



2. Draw a circuit diagram with a voltage source and three resistors connected in series. $V_{\text{source}} = 15.0$ V, $V_2 = 4.0$ V, $R_1 = 30.0\ \Omega$, and $I_2 = 0.20$ A. Find V_1, V_3, I_1, I_3, I_{source}, R_2, R_3, and R_{total}. T/I C
3. Draw a circuit diagram with a voltage source and three resistors connected in parallel. $V_{\text{source}} = 1.5$ V, $I_1 = 0.10$ A, $R_2 = 7.5\ \Omega$, and $R_3 = 5.0\ \Omega$. Find V_1, V_2, V_3, I_2, I_3, I_{source}, R_1, and R_{total}. T/I C
4. For the circuit diagram shown in **Figure 6**, $V_1 = 2.5$ V, $V_3 = 5.0$ V, $I_2 = 0.30$ A, $I_3 = 0.50$ A, $I_4 = 0.10$ A, and $R_4 = 70.0\ \Omega$. Find V_{source}, V_2, V_4, V_5, I_{source}, I_1, I_5, R_1, R_2, R_3, R_5, and R_{total}. T/I

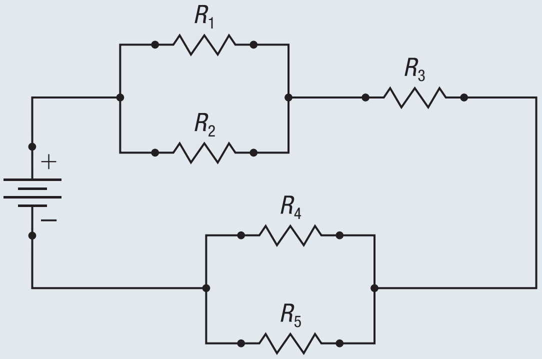


Figure 6

CHAPTER 11 Investigations

Investigation 11.8.1 OBSERVATIONAL STUDY

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Analyzing Circuits

You have learned about three quantities related to electricity: current, electric potential difference, and resistance. You have also learned about Kirchhoff's laws and how voltage and current are related in series, parallel, and mixed circuits. This Observational Study will give you an opportunity to confirm these laws through the measurement of the three electrical quantities.

Purpose

In this observational study, you will design three circuits: series, parallel, and mixed. Each circuit should contain a source, two or four loads, and a switch. You will measure all values of potential difference and current. Then you will calculate the resistance and explain the results.

Equipment and Materials

- DC power supply or battery
- 4 loads (preferably 4 different ceramic resistors ranging from 5 Ω to 20 Ω)
- switch
- voltmeter
- ammeter
- 8 to 10 leads

Procedure

SKILLS HANDBOOK A2.4, A3

Part A: Series Circuit

1. Refer to Sections 11.3 and 11.5 to review how voltmeters and ammeters are connected.
2. Design a series circuit on paper and draw a circuit diagram. Your series circuit must have two loads, a switch, and a power source. Have your teacher check your circuit before you proceed.

Always ensure that the power supply is turned off before connecting or disconnecting a circuit. Always have your teacher check your circuits before turning on the power supply.

3. Make sure that the power supply is off. Connect the circuit you have designed. Be sure to set the power supply as instructed by your teacher.
4. Construct a table to record the readings for potential difference and current from the voltmeter and ammeter. Include a column for resistance. Be sure to include measurements for the loads and the source.
5. Turn on the switch and record the potential difference across the loads and the source, and the current through the loads and the source.
6. Turn off the circuit and disassemble the leads.

Part B: Parallel Circuit

7. Design a parallel circuit on paper and draw a circuit diagram. Your parallel circuit must have two loads, a switch, and a power source. Have your teacher check your circuit before you proceed.
8. Make sure that the power supply is off. Connect the circuit as designed. Be sure to set the power supply as instructed by your teacher.
9. Construct a table to record the readings for potential difference and current from the voltmeter and ammeter. Include a column for resistance. Be sure to include measurements for the loads and the source.
10. Turn on the switch and record the potential difference across the loads and the source, and the current through the loads and the source.
11. Turn off the circuit and disassemble the leads.

Part C: Mixed Circuit

12. Design a mixed circuit on paper and draw a circuit diagram. Your mixed circuit must have four loads, a switch, and a power source. Have your teacher check your circuit before you proceed.
13. Make sure that the power supply is off. Connect the circuit as designed. Be sure to set the power supply as instructed by your teacher.
14. Construct a table to record the readings for potential difference and current from the voltmeter and ammeter. Include a column for resistance. Be sure to include measurements for the loads and the source.
15. Turn on the switch and record the potential difference across the loads and the source and the current through the loads and the source.
16. Turn off the circuit and disassemble the leads. Return all the equipment as instructed by your teacher.

Analyze and Evaluate

(a) What variables were measured in each part of the investigation? What varied between the parts of the investigation? T/I

(b) Calculate the resistance for each load and source in your circuits and enter the results in your tables. T/I

(c) For the series circuit you constructed in Part A, did the electric current value you observed confirm KCL? If not, explain any discrepancies. T/I

(d) For the series circuit, did the potential difference across the source add up to the sum of the potential differences across the loads? If not, explain any discrepancies. T/I

(e) For the series circuit, add up the resistance of all the loads. How does this compare to the total resistance? T/I

(f) For the parallel circuit you constructed in Part B, did the electric current measured confirm KCL? If not, explain any discrepancies. T/I

(g) For the parallel circuit, was the potential difference across the loads the same as the potential difference across the source? If not, explain any discrepancies. T/I

(h) Write a statement about how the total resistance compares to the resistances of the loads in the parallel circuit. Include an explanation. T/I C

(i) For the mixed circuit you constructed in Part C, how did the parallel potential differences compare to the series potential differences? T/I

Apply and Extend

(j) What would you expect the potential difference to be across a lead? Try measuring the potential difference across a lead that is connected in the circuit with a voltmeter. Explain the result of your measurement. Repeat with a switch. T/I C

(k) How did the values in the series circuit compare to the values in the parallel circuit? What do you think would happen to the current if you added another load? Try it, if time permits and you have your teacher's permission. T/I C

(l) Some of the circuits in your home are connected in parallel. Based on your findings in Question (b), predict what would happen if you connected many loads in parallel in your home. T/I C

LEARNING **TIP**

Connecting Circuits with an Ammeter

When connecting circuits with an ammeter, you must make a break in the circuit by disconnecting a wire. You then connect the ammeter in the place where you made the break.

CHAPTER 11 SUMMARY

Summary Questions

1. Create a study guide for this chapter based on the Key Concepts on page 502. For each point, create three or four subpoints that provide further information, relevant examples, explanatory diagrams, or general equations.
2. Look back at the Starting Points questions on page 502. Answer these questions using what you have learned in this chapter. Compare your latest answers with those that you wrote at the beginning of the chapter. Note how your answers have changed.

Vocabulary

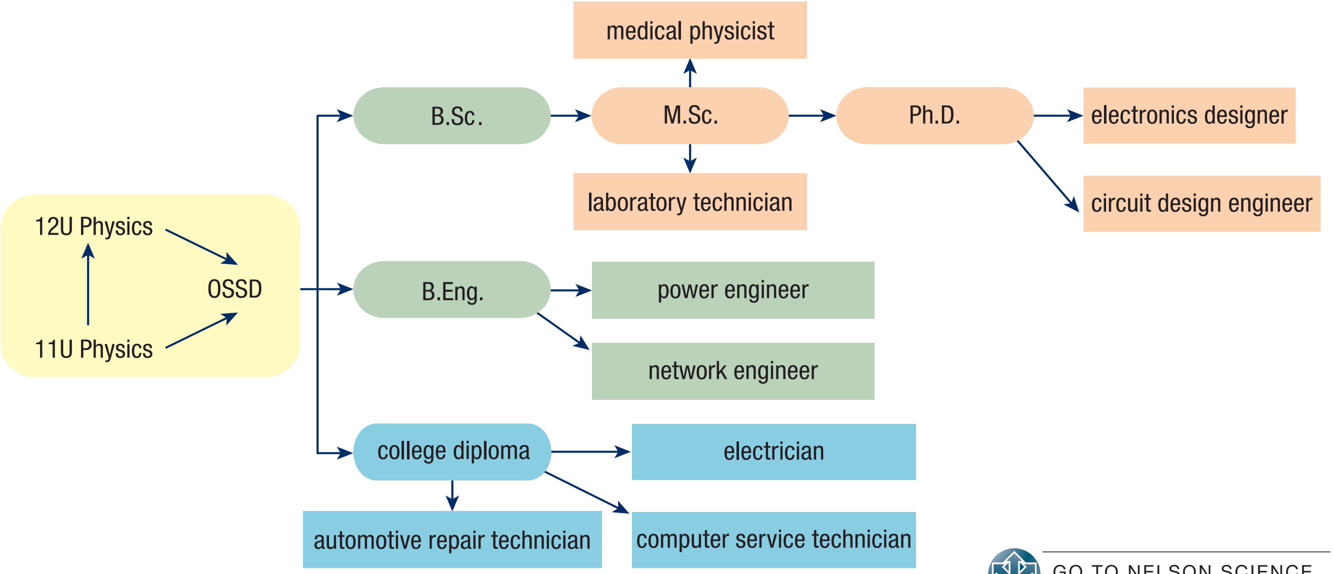
electrical power (*P*) (p. 504)
kilowatt hour (kWh) (p. 505)
electric potential (p. 511)
electric potential difference (*V*) (p. 511)
voltmeter (p. 512)
direct current (DC) (p. 516)
ammeter (p. 517)
Kirchhoff's voltage law (KVL) (p. 519)
Kirchhoff's current law (KCL) (p. 519)
electrical resistance (*R*) (p. 523)
resistor (p. 523)
Ohm's law (p. 524)
ohmmeter (p. 525)
equivalent resistance (p. 527)

CAREER PATHWAYS

SKILLS HANDBOOK A7

Grade 11 Physics can lead to a wide range of careers. Some require a college diploma, bachelor of science degree, or work experience. Others require specialized or postgraduate degrees. This graphic organizer shows a few pathways to careers related to topics covered in this chapter.

1. Select an interesting career that relates to Electricity and Its Production. Research at least two pathways that could lead to this career, and present your findings in the form of a graphic organizer similar to the one below.


12U Physics
11U Physics
OSSD
B.Sc.
M.Sc.
Ph.D.
medical physicist
laboratory technician
electronics designer
circuit design engineer
B.Eng.
power engineer
network engineer
college diploma
electrician
automotive repair technician
computer service technician

GO TO NELSON SCIENCE

CHAPTER 11 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. Which of the following is a unit of electrical energy? (11.1) K/U
   (a) watt
   (b) kilowatt hour
   (c) coulomb
   (d) ohm
2. Electric potential difference is measured in volts. Which of the following is equivalent to 1 V? (11.3) K/U
   (a) 1 I/C
   (b) 1 J·C
   (c) 1 C/J
   (d) 1 J/C
3. Which device is used to measure the current in a circuit? (11.5) K/U
   (a) ammeter
   (b) ohmmeter
   (c) voltmeter
   (d) potential meter
4. How much current moves through a wire that has 0.75 C of electrons passing through a point every 1.5 s? (11.5) T/I
   (a) 2.0 A
   (b) 0.50 A
   (c) 1.125 A
   (d) none of the above
5. What does the symbol in **Figure 1** represent in a circuit? (11.6) K/U
   (a) motor
   (b) battery
   (c) resistor
   (d) lamp

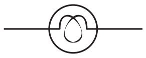


Figure 1

6. Which of the following is the correct formula for Kirchhoff's current law (KCL) for parallel loads? (11.6) K/U
   (a) $I_{\text{parallel}} = I_1 + I_2 + I_3 + \cdots$
   (b) $I_{\text{parallel}} = I_1 = I_2 = I_3 = \cdots$
   (c) $V_{\text{parallel}} = V_1 + V_2 + V_3 + \cdots$
   (d) $V_{\text{parallel}} = V_1 = V_2 = V_3 = \cdots$
7. What is resistance a measure of? (11.7) K/U
   (a) the energy of electrons in a resistor
   (b) the number of coulombs in a resistor
   (c) the difficulty for electrons to flow through a resistor
   (d) the conventional current in a resistor
8. Which of the following is the correct formula for the total equivalent resistance for resistors that are connected in parallel? (11.8) K/U
   (a) $R_{\text{parallel}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots$
   (b) $\frac{1}{R_{\text{parallel}}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots$
   (c) $R_{\text{parallel}} = R_1 + R_2 + R_3 + \cdots$
   (d) $\frac{1}{R_{\text{parallel}}} = R_1 + R_2 + R_3 + \cdots$

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

9. The most convenient unit for measuring electrical energy usage in your home is the joule. (11.1) K/U
10. Electric potential is the measure of the amount of electrical energy per coulomb of charge. (11.3) K/U
11. Conventional current and electron flow both describe the same direction of flow of charges in a circuit. (11.4) K/U
12. An ammeter must be connected in parallel with a load to measure the current through it. (11.5) K/U
13. Loads that are placed in series in a circuit all carry the same current. (11.6) K/U
14. Resistance in a wire will cause some of the electrical energy to be converted to thermal energy. (11.7) K/U
15. The total resistance for resistors connected in series is the sum of their resistances. (11.8) K/U

To do an online self-quiz,
GO TO NELSON SCIENCE

Knowledge

For each question, select the best answer from the four alternatives.

1. Which of the following is a unit of electrical power? (11.1) K/U
   (a) joule
   (b) watt
   (c) kilowatt hour
   (d) coulomb
2. What are you measuring when you measure voltage in a circuit using a voltmeter? (11.3) K/U
   (a) the amount of energy of individual electrons
   (b) the difference in the amount of energy associated with a coulomb of electrons between two points in a circuit
   (c) the difference in the number of electrons between two points in a circuit
   (d) the difference in the flow of electrons between two points in a circuit
3. A hydroelectric power plant transforms which of the following into electrical energy? (11.1) K/U
   (a) nuclear energy
   (b) thermal energy
   (c) kinetic energy
   (d) solar energy
4. Which of the following devices uses the most power? (11.1) K/U
   (a) plasma TV
   (b) cellphone
   (c) laptop computer
   (d) central air conditioner
5. Which type of power plant technology is least efficient? (11.1) K/U
   (a) fossil fuel
   (b) solar
   (c) hydro
   (d) nuclear
6. Which device is used to measure the electric potential difference in a circuit? (11.3) K/U
   (a) ammeter
   (b) ohmmeter
   (c) voltmeter
   (d) potential meter
7. When an electric current is present in a circuit, which particles move? (11.5) K/U
   (a) electrons
   (b) protons
   (c) neutrons
   (d) all of the above
8. What electrical component does the symbol in **Figure 1** represent? (11.6, 11.7) K/U
   (a) connecting wire
   (b) battery
   (c) lamp
   (d) resistor

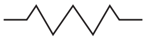


Figure 1

9. Which of the following expressions is equivalent to resistance? (11.7) K/U
   (a) $V \times I$
   (b) $\frac{I}{V}$
   (c) $\frac{V}{I}$
   (d) $\frac{1}{IV}$

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

10. Burning coal can cause global warming and acid rain. (11.2) K/U
11. Coal gasification is a technology that captures carbon dioxide leaving the smokestack, compresses it, and transports it by pipeline to a storage location deep underground. (11.2) K/U
12. Electric potential is a measure of how much electric potential energy is associated with each charge. (11.3) K/U
13. Conventional current is the movement of charge from negative to positive. (11.4) K/U
14. Direct current is the flow of electrons in a back-and-forth manner through a circuit. (11.5) K/U
15. The symbol I is used to represent electric current. (11.5) K/U

16. Kirchhoff's current law (KCL) states that the current entering a junction is equal to the current exiting a junction in a circuit. (11.6) K/U

17. Superconductors are materials with almost infinite electrical resistance. (11.7) K/U

18. For resistors in series, the total resistance is given by $\frac{1}{R_{\text{series}}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots$ (11.8) K/U

Write a short answer to each question.

19. A circuit consists of three loads connected in series. Using one of Kirchhoff's laws, express the potential difference across the voltage source in terms of the potential differences across each of the loads. (11.6) K/U

20. Three resistors, R_1, R_2, and R_3, are placed in parallel. Write an expression for the total resistance, R, of the circuit. (11.8) K/U

21. Draw the circuit symbol that represents a battery. (11.6) K/U

Understanding

22. A nuclear power plant has an efficiency of 35 %. If the core nuclear reactants can provide 12 000 MW of power, how much electrical power does the power plant produce? (11.1) T/I

23. Calculate the energy, in kilowatt hours, required by a 60.0 W light bulb that operates for 3.0 h. (11.1) T/I

24. Calculate the energy, in kilowatt hours and joules, needed by a 450 W window air conditioner that operates for 48 h. (11.1) T/I

25. Calculate the amount of power required to charge a battery if 1200 J of energy is transferred in 5 min. (11.1) T/I

26. A solar power plant has an efficiency of 16 % and produces 30.0 MW of electrical power. (11.1) T/I
    (a) How much total power does the power plant require as input in order to produce an output of 30.0 MW?
    (b) How much energy is lost by being converted to thermal energy each second?

27. Calculate the electric potential difference between the negative and positive terminals of a battery if 1080 J of electric potential energy is transformed to move 120 C of charge between the terminals. (11.3) T/I

28. The potential difference across the terminals of a light bulb is 120 V. If the bulb transforms 480 J of energy, how much total charge is moved across the terminals? (11.3) T/I

29. A 35 W light bulb is on for 2.5 h. If the potential difference across the bulb's terminals is 120 V, how much total charge moves through the bulb while it is on? (11.1, 11.3) T/I

30. Redraw the circuit in **Figure 2** to include the placement of an ammeter to measure I_3, a voltmeter to measure V_2, and an ohmmeter to measure R_1. (11.3, 11.5, 11.7) T/I C

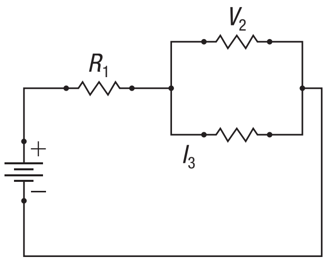


Figure 2

31. A washing machine is plugged into a 240 V source and uses 2.0 kWh of energy each load. (11.1, 11.3, 11.5) T/I
    (a) How much total charge is moved through the machine for each load?
    (b) If each load takes 35 min, how much power does the machine use? Answer in watts.
    (c) If each load takes 35 min, how much current does the machine draw? Answer in amperes.

32. A student has connected an ammeter into a circuit as shown in **Figure 3**. Redraw the figure to show a proper connection for an ammeter. (11.5) T/I C

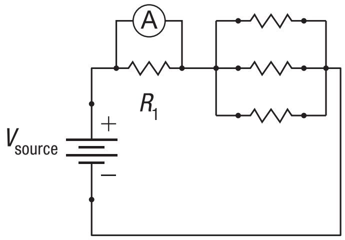


Figure 3

33. Calculate the amount of current in a wire if 0.75 C of electrons pass through a point in 1.7 min. (11.5) T/I

34. How many coulombs pass through a wire that carries a current of 3.2 A for 5.0 h? (11.5) T/I

35. Calculate the time required for 3 C of charge to pass through a resistor if the current is 750 mA. (11.5) T/I

36. Draw a circuit with a battery and two lamps in parallel. (11.6) K/U C

37. Draw a circuit with a battery and a lamp that is in series with two resistors that are in parallel. (11.6) K/U C

38. In the circuit in **Figure 4**, if the potential difference across the battery is 9.0 V, calculate V_2 if
   (a) $V_1 = 3.0$ V
   (b) $V_1 = V_2$ (11.6) T/I

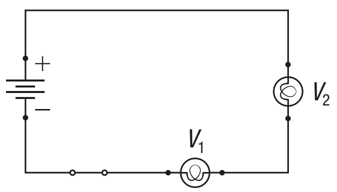


Figure 4

39. In the circuit in **Figure 5**, $I_1 = 7.5$ mA. Calculate I_3 if
   (a) $I_2 = 4.3$ mA
   (b) $I_2 = I_3$ (11.6) T/I

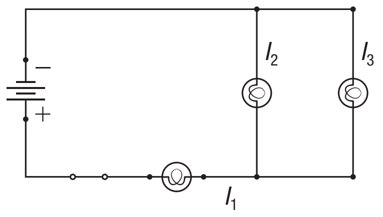


Figure 5

40. Calculate the resistance of a load with a voltage of 60 V and a current of 750 mA. (11.7) T/I

41. An 80.0 Ω resistor carries 0.85 mA of current. What is the potential difference across the resistor? (11.7) T/I

42. The circuit in **Figure 6** has a current of 0.50 mA. If V_1 is 4.55 V and the potential difference across the battery is 12 V, what are the two resistances, R_1 and R_2? (11.7) T/I

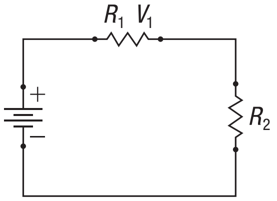


Figure 6

43. Four resistors are placed in series in a circuit. If the resistances are $R_1 = 2.3\ \Omega$, $R_2 = 4.3\ \Omega$, $R_3 = 0.85\ \Omega$, and $R_4 = 1.2\ \Omega$, what is the total resistance of the circuit? (11.8) T/I

44. Three resistors are connected in parallel in a circuit. If the resistances are $R_1 = 2.1\ \Omega$, $R_2 = 7.2\ \Omega$, and $R_3 = 4.5\ \Omega$, calculate the equivalent resistance of the circuit. (11.8) T/I

45. Calculate the total resistance in the circuit in **Figure 7** if the resistor values are as follows: $R_1 = 6.1\ \Omega$, $R_2 = 13\ \Omega$, and $R_3 = 27.2\ \Omega$. (11.8) T/I

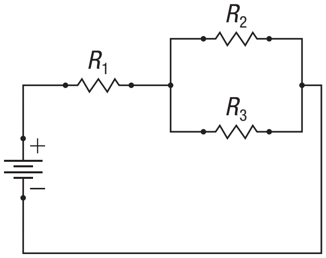


Figure 7

46. In the circuit in **Figure 8**, the potential difference across the battery is 18 V. V_1 is 7.0 V and $R_2 = 30.0\ \Omega$. Calculate the values of R_1, V_2, and the current through the circuit. (11.9) T/I

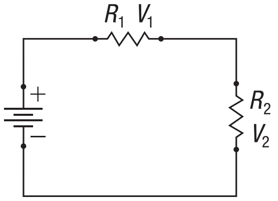


Figure 8

47. For the circuit in **Figure 9**, $R_1 = 3.0\ \Omega$ and $R_2 = 60.0\ \Omega$. The potential difference across the battery is 22 V, and V_1 is 12 V. Calculate I_1, I_2, I_3, and R_3. (11.9) T/I

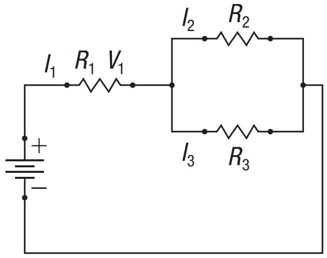


Figure 9

Analysis and Application

48. (a) A hydroelectric power plant produces 1200 MW of power at 85 % efficiency. A nuclear power plant produces 1200 MW of power at 40 % efficiency. How much more power is wasted in the nuclear power plant than in the hydroelectric power plant?
    (b) It is difficult to compare the efficiencies of different power plants because some plants transform energy twice: the first time from the source energy to thermal energy and the second time from thermal energy to electrical energy. Name two power plant technologies that can be compared more directly. (11.1) T/I A
49. A coal-fired power plant produces 2500 MW of power with 46 % efficiency. When carbon capture technology is installed, the efficiency decreases to 42 %. Calculate the amount of extra power lost to the carbon capture technology. (11.1, 11.2) T/I A
50. A battery takes 2.0 MJ of energy to charge. If the charger operates using 40.0 W of power but only transfers 90 % of the energy to the battery, how long does it take to charge the battery? (11.1) T/I
51. A 60.0 W incandescent light bulb is only 11 % efficient at producing light (the rest is converted into thermal energy). The light bulb is operating for 2.0 h. Calculate how much energy is input to the bulb and how much energy is output as light energy. (11.1) T/I
52. A 14 W CFL bulb uses 5.1 kWh of electrical energy at an efficiency of 75 %. Calculate the time that the CFL bulb is operational and the electrical energy output. Answer in hours and kilowatt hours respectively. (11.1) T/I
53. In the circuit in **Figure 10**, $V_{\text{source}} = 20.0$ V, $R_1 = 30.0\ \Omega$, and $R_2 = 12.0\ \Omega$. In 10.0 s, how many coulombs of charge pass through the circuit? (11.5, 11.9) T/I

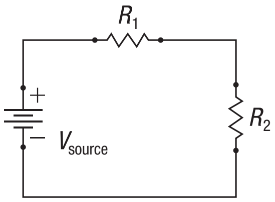


Figure 10

54. In the circuit in **Figure 11**, $V_{\text{source}} = 5.0$ V, $R_1 = 7.0\ \Omega$, and $V_2 = 3.55$ V. (11.5, 11.9) T/I
    (a) What is the value of R_2?
    (b) How long will it take for 12 C of charge to pass through the circuit?

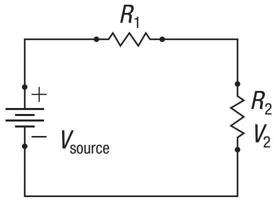


Figure 11

55. In the circuit in **Figure 12**, $V_{\text{source}} = 12$ V, $R_1 = 5.0\ \Omega$, $R_2 = 16\ \Omega$, and $R_3 = 30.0\ \Omega$. (11.5, 11.9) T/I
    (a) After 7.0 s, how many coulombs of charge pass through the circuit?
    (b) After 12 s, how many coulombs of charge pass through R_2?

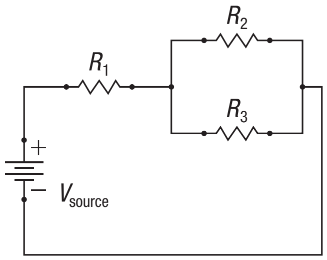


Figure 12

56. In the circuit in **Figure 13**, $V_{\text{source}} = 15$ V, $V_1 = 9.0$ V, $I_3 = 500.0$ mA, and $R_2 = 30.0\ \Omega$. (11.5, 11.9) T/I
    (a) What are R_3 and I_2?
    (b) How long does it take for 20.0 C of charge to pass through the circuit?

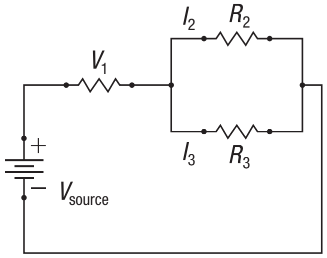


Figure 13

57. A repair technician is using an ohmmeter to check for open circuits in a computer system. The computer system is connected to a power supply that is turned on. The technician records resistance values and then turns the power supply off. He then repeats his measurements of resistance values. Would the resistance values be the same in both measurements? Which scenario is correct for measuring resistance values? (11.7) T/I

58. A student has three resistors, with resistances of 75 Ω, 50 Ω, and 30 Ω. Draw a diagram to show how the student can build a circuit with a total resistance of 60 Ω. (11.8) T/I C

59. A student has four resistors, with resistances of 7.00 Ω, 12.0 Ω, 24.0 Ω, and 28.0 Ω. Draw a diagram to show how the student can build a circuit with a total resistance of 13.6 Ω. (11.8) T/I C

60. Derive an expression for power (P) in terms of current (I) and potential (V). (11.1, 11.3, 11.5, 11.7) T/I C

61. A student measures the following values for voltage across and current through a circuit:

Current (I)	Potential (V)
0.080 mA	10 V
0.097 mA	12 V
0.111 mA	14 V
0.129 mA	16 V
0.144 mA	18 V

(a) Plot the points on a graph of voltage versus current. Draw the line of best fit.
(b) What is the slope of the line of best fit and what does it mean? (11.8) K/U T/I C

62. In the circuit in **Figure 14**, $R_1 = 30.0\ \Omega$, $R_2 = 50.0\ \Omega$, $R_3 = R_4 = 60.0\ \Omega$, and $V_1 = 12$ V. (11.9) T/I
(a) What is the total current through the circuit?
(b) What is V_{source}?

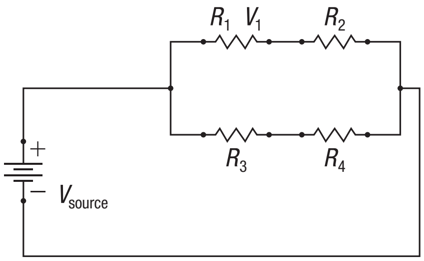


Figure 14

63. In the circuit in **Figure 15**, $R_1 = R_2$, $R_3 = 150\ \Omega$, and $R_4 = 200.0\ \Omega$. If $V_{\text{source}} = 15$ V and $I_1 = 4.0$ A, find
(a) R_1 and R_2
(b) I_3 (11.9) T/I

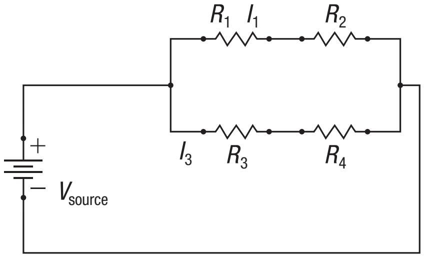


Figure 15

64. In the circuit in **Figure 16**, $V_1 = V_4$, $V_{\text{source}} = 50.0$ V, $R_1 = 100.0\ \Omega$, $R_2 = 2R_3$, $I_{\text{source}} = 0.250$ A, and $2I_2 = 3I_4$. (11.9) T/I
(a) What are the values of R_4, I_1, I_2, and I_4?
(b) What are the values of V_2 and V_3?

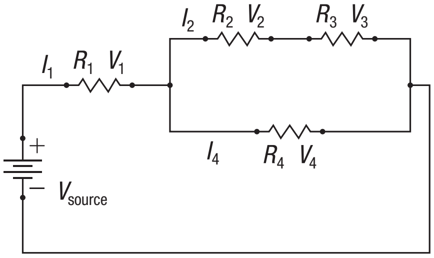


Figure 16

65. In the circuit in **Figure 17**, $R_2 = 2R_3$, $R_1 = R_4$, $2R_1 = 5R_3$, $V_{\text{source}} = 34$ V, and $I_1 = 110$ mA. (11.9) T/I
(a) Find the values of R_1, R_2, R_3, and R_4.
(b) Find I.

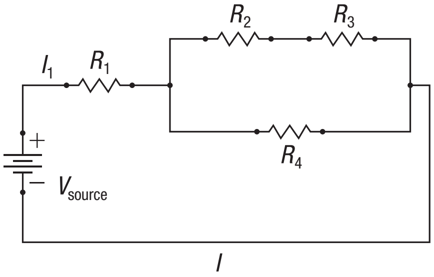


Figure 17

Evaluation

66. Make a list of five common household items that use electricity, and determine the average voltage, current, and resistance for each by looking at the label. Rank these items in order of the energy they consume in one day of average use in your household. (11.3, 11.5, 11.6) T/I C A

67. A common household outlet has a small night light plugged into the top part of the receptacle. A power bar is plugged into the bottom part of the receptacle, and plugged into the power bar are a lamp, a computer, and a cellphone charger. Draw a circuit diagram for this outlet. Use resistor symbols for the computer and cellphone charger and be sure to label all parts. Why might it be a poor idea to include the lamp and cell phone charger on the same power bar as the computer? (11.7, 11.8) T/I C A

Reflect on Your Learning

68. More than half of Ontario's electrical energy is generated through nuclear power. Do you approve or disapprove of using this technology to produce your electricity? Would you rather use an alternative source of energy? Write several paragraphs supporting your view on how electrical energy should be produced in Ontario. K/U C A

69. Making power plants more efficient is an ongoing and expensive process. Suggest things that you could do at home to reduce your dependence on electricity. K/U C A

70. Electric potential difference is a challenging concept for students to grasp. What aspects did you find challenging and what helped you gain a deeper understanding? K/U C

71. What aspect of Kirchhoff's voltage law did you find particularly challenging? Explain what helped you get past your difficulties. K/U C

72. Connecting resistors in parallel lowers the total or equivalent resistance. Many students find it challenging to understand how the addition of resistors in parallel can lower the equivalent resistance. How have you come to understand this concept? K/U C

Research

GO TO NELSON SCIENCE

73. You can purchase several different types of light bulbs to use at home. Research and compare the environmental impacts of compact fluorescent, incandescent, and LED technologies. T/I C A
    (a) What materials are used to make each light bulb? Are there environmental concerns about these materials?
    (b) Compare the amount of energy used in a 10-year period for each light bulb. Which bulb has more of an environmental impact over the 10-year period?
    (c) What are the environmental impacts of disposing of the light bulbs? Do they require special treatment? Which type of bulb produces the most waste?

74. Resistors are used in virtually every electronic device. Research the different types of resistors. Find out what they look like, what they are made of, what their resistance is, how they are labelled, and what they are used for. Summarize your research in a report or poster. T/I C A

75. One of the most overlooked pollutants from power plants is waste heat that is generally given off into bodies of water. If the average temperature of that body of water increases by even a few degrees, it can have major effects on the ecosystem. Research the average amount of waste heat that different power plants may produce and the environmental impacts that are being dealt with today. T/I C A

76. Determine the average potential difference in a bolt of lightning. What causes this potential difference, and how much current can a bolt of lightning carry? Find an estimate for the average duration of each type of bolt and determine the total charge carried. Include theories for the causes of each type of lightning. T/I C A

77. The oceans are often overlooked as energy sources, but with development of new technologies, clean energy can be generated using both the tides and ocean currents. Research these new technologies. Discuss any effects these technologies may have on the environment, and decide whether they are feasible methods of energy production. T/I C A

12.1 Magnetic Fields

Imagine reaching a speed of 431 km/h on your way to the airport. The Maglev train in Shanghai, China (**Figure 1**), can do just that. "Maglev" is short for magnetic levitation. Magnets are used to apply a force to the train to lift or "levitate" it against the force of gravity. The train is then able to float above the tracks, not making physical contact. This greatly reduces friction, so the train is able to travel at very high speeds. This technology would not have been possible without an understanding of magnetism and magnetic fields.

Figure 1 This train uses magnetic levitation to float above the tracks and avoid friction.

magnetic field a region of space around a magnet that causes a magnetic force on magnetic objects

What Are Fields?

You may have heard of force fields in science-fiction games, shows, or movies. These force fields are generally invisible areas that prevent a character from entering a place or prevent weapons from harming a person or a ship. These science-fiction force fields do not exist. However, force fields are all around us. A field is a region of space surrounding an object that can cause another object to experience a force. For example, a **magnetic field** is the three-dimensional region of space surrounding a magnet that will exert a force on magnetic objects. The magnetic field exists around the magnet whether the magnetic field is causing a force or not.

Earth has a magnetic field that exists both inside and surrounding it (**Figure 2**). Other types of fields also exist in nature. A gravitational field exists around Earth because of Earth's mass, and it causes objects with mass to be attracted toward Earth's centre. Electric fields surround charged particles such as protons and electrons. The electric fields cause charged particles to experience forces of attraction or repulsion. For example, an electron has an electric field around it that will cause a force of attraction to a positively charged particle. All fields have specific properties and point in specific directions, governing how objects are affected within those fields.

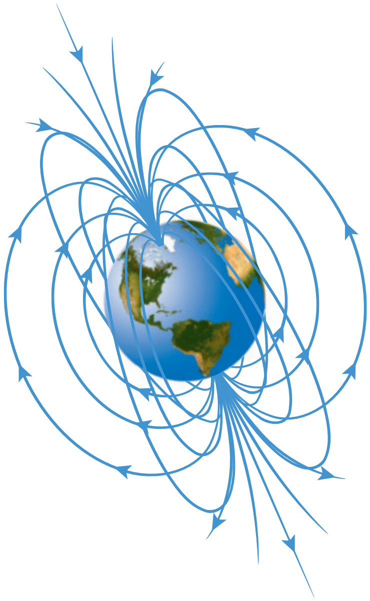


Figure 2 A magnetic force field exists both inside and surrounding Earth.

Magnetic Field Properties

There is a story about a shepherd named Magnes, who lived in the area of Magnesia, Greece, over 4000 years ago. He was surprised one day when he stepped on a rock and the iron nails in his sandals stuck to it. This type of rock came to be known as magnetite.

After more observations of magnetite, it was found that certain ends of pieces of magnetite would attract each other, while others would repel each other. This became more obvious if the magnetite was split into small slivers. When a magnetite sliver is suspended on a string, it orients itself with Earth's magnetic field. Since these slivers had two magnetic ends, they were labelled poles. This discovery led to the invention of the compass, a very useful navigational tool. The compass needle is a permanent magnet. The pole of a magnet that points toward Earth's north magnetic pole is labelled north. The other pole is labelled south. Unlike poles (north and south) attract each other, and like poles (north and north or south and south) repel each other. The force of repulsion or attraction increases as the magnets get closer to one another.

Since the north pole of the compass needle points north, it means that Earth's north pole must actually be a south magnetic pole. Similarly, Earth's south pole must actually be a north magnetic pole. In fact, Earth's magnetic poles have actually flipped directions in the past. Approximately 780 000 years ago, the north pole slowly moved toward the south pole until the poles changed over. Today, scientists have noticed a steady decline in the strength of Earth's magnetic field. Some scientists believe that another flip is coming soon, perhaps in the next 1000 years.

Magnetic Field Lines

Magnetic fields exist in three dimensions surrounding a magnet and are more intense at the poles. Magnetic fields are invisible, but can be represented in diagrams with magnetic field lines. Magnetic field lines

- point from the north pole to the south pole outside a magnet, and from the south pole to the north pole inside a magnet
- never cross one another
- are closer together where the magnetic field is stronger

Drawing Field Lines

A compass can be used to map the direction of the field lines around a magnet. The compass needle will align itself along the direction of the field. **Figure 3** shows the field lines around different magnets.

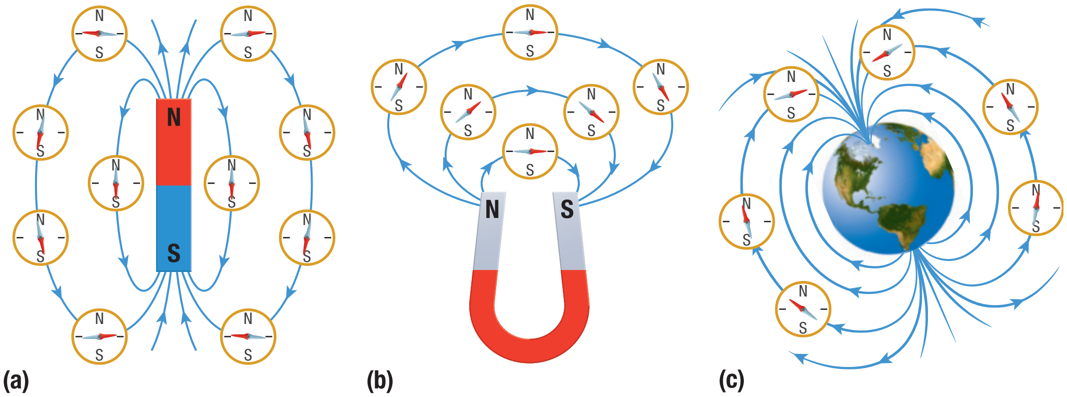


Figure 3 (a) A magnetic field around a bar magnet with mini compasses on the field lines (b) A magnetic field around a horseshoe magnet with mini compasses on the field lines (c) A magnetic field around Earth with mini compasses on the field lines

When the north pole of a magnet is brought near the south pole of another magnet, the two magnets attract each other. This happens because of the way the magnetic field of one magnet interacts with the magnetic field of the other magnet. The field lines appear as shown in **Figure 4**.

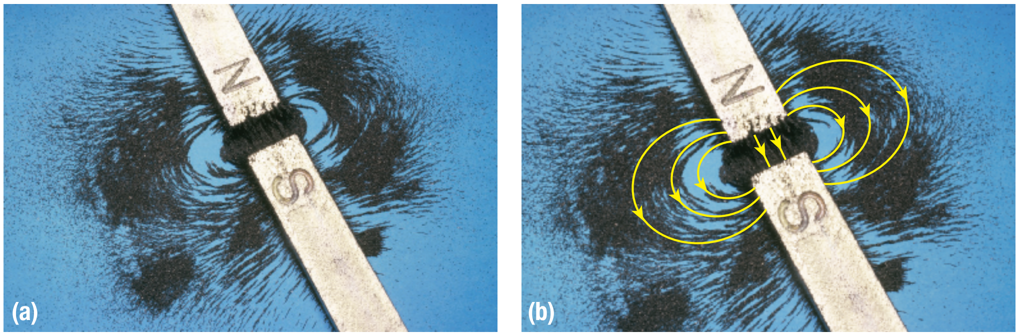


Figure 4 (a) The magnetic fields around these magnets are shown using iron filings, which line up with the field lines. (b) The direction of the magnetic field lines

When two like magnetic poles (north and north or south and south) are brought close to one another, the magnets repel each other. This happens because of the way the magnetic fields of the magnets interact. The magnetic fields appear as shown in **Figure 5**.

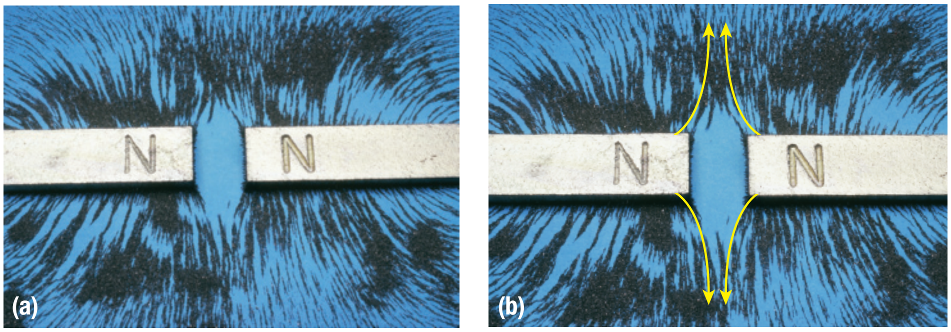


Figure 5 (a) The magnetic fields around these magnets are shown using iron filings, which line up with the field lines. (b) The direction of the magnetic field lines

Investigation 12.1.1

Properties of Magnetic Fields (p. 574)
In this investigation, you will observe the properties of the magnetic fields around permanent magnets.

Magnetic Fields at Work

Many technologies, such as Maglev trains, particle accelerators, and magnetic resonance imaging (MRI) systems, use magnetic fields. The Maglev train discussed in the opening paragraph uses magnetic fields for both levitation and forward motion. The type of Maglev train used in Shanghai is based on a German design that uses magnetic fields that cause the train to levitate based on attraction. The bottom of the train is attracted upward toward the bottom of the track (**Figure 6**). The forward motion is caused by both attraction and repulsion forces between the track and the train. Attraction forces between the front of the train and the track immediately in front of it pull the train forward. At the same time, repulsion forces at the back of the train push it forward.

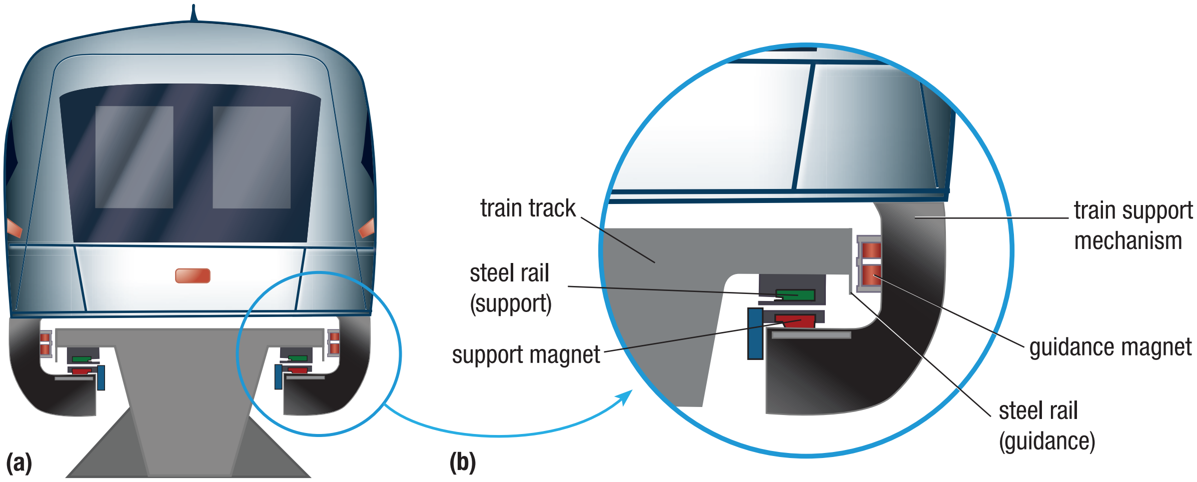


Figure 6 (a) The Maglev train support mechanism (b) The red support magnet attracts upward toward the bottom of the steel rail. This levitates the train at all times. The guidance magnet is used to keep the train along a specific path as it moves above the track.

Particle accelerators are machines that accelerate subatomic particles, such as electrons and protons, to speeds approaching the speed of light, making them collide with a target or with other particles. The results of the collisions are analyzed to possibly find new particles. The Large Hadron Collider (LHC) is a particle accelerator in Europe that uses magnetic fields to control the path and speed of protons. Scientists force the protons to collide with each other. One of the aims of the LHC is to detect a special particle called the Higgs boson, which is believed to be responsible for the mass of all particles.

A magnetic resonance imaging (MRI) system uses incredibly strong magnetic fields to produce very detailed images of the inside of the human body. These detailed images provide doctors with important information that can be used to diagnose a disease or provide information for surgery. MRI scans can even detect cancerous cells before they become tumours. Early detection and diagnosis of problems can help save many lives.

These amazing technologies use magnetic fields, but magnetic fields are also found in many technologies that we use daily. Magnetic fields are present wherever there is a magnet. Magnets can hold pictures on the side of a refrigerator, or in your locker at school; magnets inside electric motors help the motors spin; electric bells use magnets to ring at the end of your physics class; and the hard drive in your computer stores information using magnetic fields.

In the northern parts of the northern hemisphere, magnetic fields cause beautiful displays of light in the night sky called northern lights or aurora borealis (**Figure 7**). Charged particles from the Sun travel through space and interact with Earth's magnetic field, which is strongest at the poles. The shape of the field directs these charged particles toward the ground. These downward-travelling particles collide with oxygen or other gases in the atmosphere, transforming kinetic energy into light.

Even living creatures can use magnetic fields to their benefit. Spiny lobsters navigate their way through long migrations over hundreds of kilometres. Scientists suspected that the spiny lobsters used Earth's magnetic field to guide their way. They removed some lobsters and placed them in a tank where the scientists could slightly change the magnetic field. With the magnetic field changed, the lobsters changed their path. Other animals, like birds, also use the magnetic field of Earth to help navigate while migrating.

CAREER LINK

To learn more about becoming a particle physicist,

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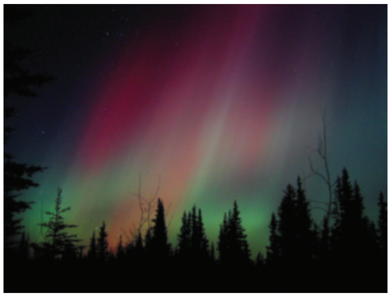


Figure 7 Northern lights produced as a result of Earth's magnetic field interacting with charged particles from the Sun in the atmosphere. The different colours result from collisions with oxygen, nitrogen, hydrogen, and helium at different altitudes.

WEB LINK

To find out more about how living creatures use magnetic fields,

GO TO NELSON SCIENCE

Research This

The Maglev Train

Skills: Researching, Analyzing, Communicating

SKILLS HANDBOOK A5.1

Mass transit is one solution that has been recommended to lessen the amount of greenhouse gases we emit by reducing the number of cars and trucks on the road. High-speed mass transit could reduce the use of airplanes, which also emit greenhouse gases. The Maglev train is one option.

1. Research the operational Maglev train in Shanghai and collect information on the benefits and disadvantages.
2. Research conventional trains and collect information on the benefits and disadvantages.
3. Research future projects that plan to use Maglev technology.

A. What is the main advantage of Maglev technology? T/I

B. What are some reasons why Maglev train technology is not more commonly used? T/I

C. Compare conventional train technology to Maglev technology using a graphic organizer. T/I C A

D. How has Maglev technology affected the people who use the Maglev train in Shanghai? How has its use affected the environment? T/I A

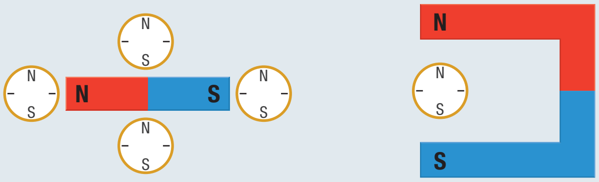
GO TO NELSON SCIENCE

12.1 Summary

- Magnetic fields cause forces on objects that can be affected by magnets.
- Magnetic fields are three-dimensional.
- Magnetic forces increase as magnetic objects get closer to each other.
- Magnetic fields cause attraction between unlike poles and repulsion between like poles.
- Magnetic field lines represent what a magnetic field looks like around a magnetic object.
- Magnetic field lines point from the magnetic north pole to the magnetic south pole outside a magnet and from south to north inside a magnet.
- Magnetic field lines never cross one another.
- Magnetic field lines are closer together where the magnetic field is stronger.

12.1 Questions

1. Describe the importance of the compass to navigation. K/U C A
2. How would moving the magnetic north pole of Earth to a point on the equator change navigation using a compass? K/U
3. You come across a piece of magnetite in Ontario. Describe how you could use the magnetite to help you determine the orientation of magnetic north and magnetic south. Will you be able to determine which way is magnetic north using the magnetite? Explain your answer. K/U C A
4. Suppose Earth had no magnetic field. K/U A
   (a) How would the northern lights be affected?
   (b) What would happen to animal navigation?
5. Copy the diagrams in **Figure 8** into your notebook and show the directions that the compass needles would point. K/U T/I C



(a) **(b)**

Figure 8

6. Copy the diagrams in **Figure 9** into your notebook and show the field lines. K/U T/I C

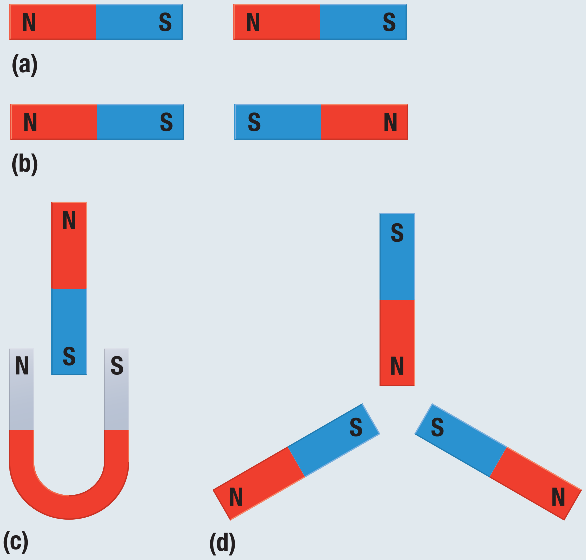


Figure 9

7. Choose one application of magnetic fields and research how they are used. Prepare a brief summary of your findings in a short report or poster. C A

GO TO NELSON SCIENCE

Oersted's Discovery

Is there a link between electricity and magnetism? Charged particles behave in a similar way to magnetic poles. Like charges (positive and positive or negative and negative) repel each other and unlike charges (positive and negative) attract each other. In 1819, Danish physicist Hans Christian Oersted was the first scientist to successfully connect electricity and magnetism. We have since found out that the electromagnetic force is one of the four fundamental forces of nature.

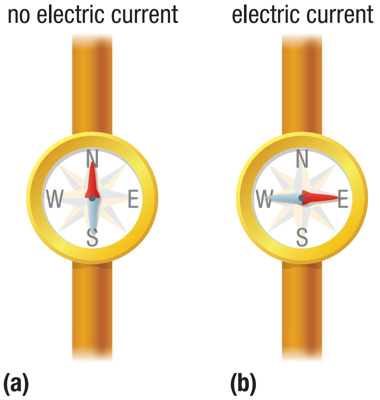


Figure 1 (a) Compass direction with no electric current. The compass and the wire are aligned with Earth's magnetic north pole. (b) Compass direction with an electric current in the wire

Oersted's Experiment

Before Oersted, many physicists had hypothesized that magnetic fields could be created by an electric current in a wire. Oersted hypothesized that the current would produce a magnetic field that radiated away from the wire. He tested his hypothesis with a compass held near a conducting wire in an electric circuit. He placed the compass so that it aligned with the wire, which, in turn, was aligned with Earth's magnetic field (**Figure 1(a)**). When an electric current was present in the wire, the compass needle was deflected perpendicular to the wire (**Figure 1(b)**). When the current in the circuit was switched off, the compass needle went back to its original position. When the electric current was reversed, the compass needle was deflected in the opposite direction.

Further investigation led to an understanding of the shape of the magnetic field around a conductor. The magnetic field surrounds the conductor in the shape of concentric circles (**Figure 2**). The direction of the magnetic field depends on the direction of the current. Reversing the direction of the electric current also reverses the direction of the magnetic field. It was also noted that the strength of the magnetic field gets weaker farther away from the conducting wire.

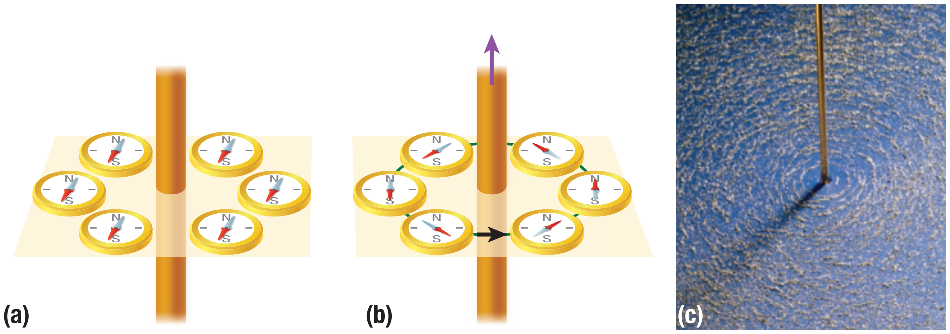


Figure 2 (a) When no electric current is present in the wire, the compasses point toward Earth's magnetic north pole. (b) When an electric current is directed up the wire, the compasses follow the circular magnetic field. (c) Iron filings around a copper wire with an electric current

In Oersted's time, the prevailing theory assumed that electric current was directed from the positive terminal to the negative terminal of a power source. Many of the rules of electromagnetism were therefore developed using the conventional current model. Hence, the magnetic field shown in Figure 2(b) is for a conventional current moving from the bottom to the top of the wire. It is important to understand that the magnetic field around the wire is independent of whether you use the conventional current model or the electron flow model.

Oersted developed a principle that describes the magnetic field around a current-carrying conductor. **Oersted's principle** states that a charge moving through a straight conductor produces a circular magnetic field around the conductor.

Oersted's principle whenever a charge moves through a straight conductor, a circular magnetic field is created around the conductor

Applying Oersted's Principle

right-hand rule for a straight conductor if you hold a straight conductor in your right hand with your right thumb pointing in the direction of the conventional current, your curled fingers will point in the direction of the magnetic field lines

A learning tool was developed to help determine the direction of the magnetic field around a straight current-carrying conductor. The **right-hand rule for a straight conductor** states that if a straight conductor is held in your right hand with your right thumb pointing in the direction of the conventional current, your curled fingers will point in the direction of the magnetic field lines surrounding the conductor (**Figure 3**).

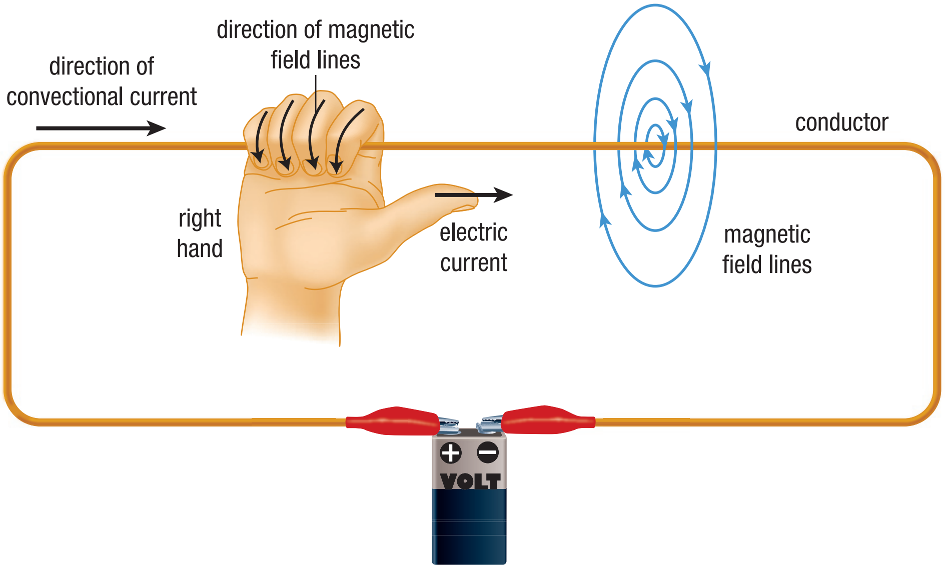

direction of convectional current
direction of magnetic field lines
conductor
right hand
electric current
magnetic field lines
VOLT

Figure 3 The right-hand rule for a straight conductor

LEARNING **TIP**

Magnetic Field Direction
Regardless of whether you use the conventional current direction or the electron flow direction to determine which way the current travels, the magnetic field around a current-carrying wire is the same.

Conventional Current versus Electron Flow

You may wonder why conventional current is used when science has demonstrated that the electron flow model is accurate for conducting wires in circuits. Physicists have chosen to use conventional current because you would expect charge to flow from where there is an excess of charge to where there is a deficit of charge. Recall from Section 11.4 that Benjamin Franklin chose positive to represent excess charge. As a result, conventional current models the flow of charges from positive to negative. With conventional current, you use your right hand to determine the direction of the magnetic field.

If you want to use the electron flow model instead, then you must use your left hand. Imagine a corresponding left-hand rule for a straight conductor. It is similar, except your left thumb follows the direction of electron flow. The fingers of your left hand still curl in the direction of the magnetic field lines. The direction of the magnetic field is the same whether you use the right-hand rule or the left-hand rule. Try using the left-hand rule as shown in **Figure 4** to confirm this.

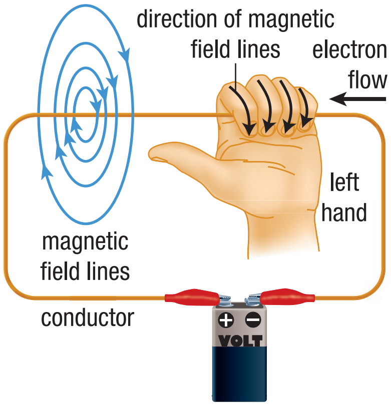


Figure 4 The left-hand rule for electron flow in a straight wire, showing the direction of the magnetic field lines. Notice that the direction of the magnetic field lines is the same in Figure 3 and Figure 4**.**

Representing Currents and Magnetic Fields

There are many different ways to represent a wire with a conventional current present in it. You can draw the wire in a three-dimensional way, as in Figure 3 and Figure 4. You can also draw the wire as a cross-section. To keep the drawing simple, the current can go into the page or out of the page. To represent a conventional current going into the page we use an X (**Figure 5(a)**), and to represent a conventional current coming out of the page we use a dot (**Figure 5(b)**). This model is based on an arrow. Imagine an arrow travelling away from you—you would see the tail in the shape of an X. If the arrow were travelling toward you, you would see the point of the arrow in the shape of a dot. Note how the concentric circles representing the magnetic field are farther apart as you move away from the wire in Figure 5. The greater spacing represents the weaker strength of the magnetic field as you move away from the wire.

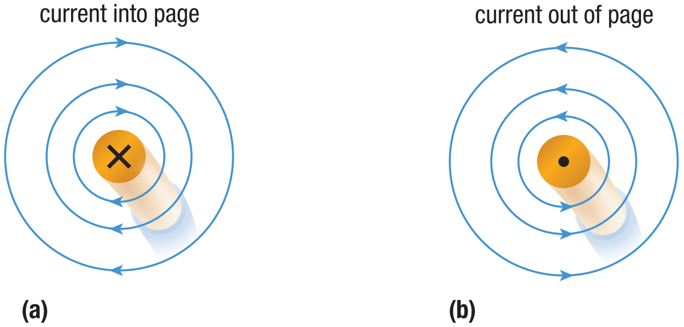


Figure 5 (a) The X represents current in a conductor moving into the page, and the blue concentric circles show the direction of the magnetic field. (b) The dot represents current in a conductor moving out of the page, and the blue concentric circles show the direction of the magnetic field.

Another method for showing the direction of the magnetic field is to use a compass. If you place the compass on top of the wire, the wire will be obscured by the compass. If you place the compass below the wire, the wire will obscure the compass (**Figure 6**).

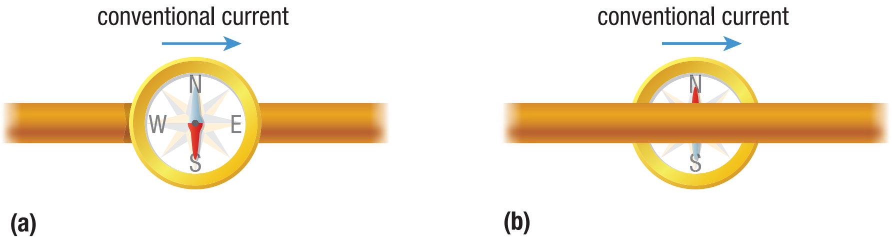


Figure 6 (a) The compass is on top of the wire with the magnetic field pointing downward. (b) The compass is underneath the wire with the magnetic field pointing upward.

Using the right-hand rule, your thumb points to the right. Imagine grabbing the wire; use your pencil as a substitute. Notice that your fingers are pointing down if they are in front of the pencil and up if they are behind the pencil.

Implications of Oersted's Discovery

Oersted's discovery forever changed the world, leading to new kinds of technologies, such as motors and generators. He demonstrated that we could use electricity to produce magnetism. Controlling magnetism means that we can turn it on and off and change its strength by increasing or decreasing the current. We can also control the direction of the magnetic field by changing the direction of the electric current.

12.2 Summary

- Hans Christian Oersted discovered that an electric current in a conductor produces a magnetic field around the conductor.
- Oersted's principle states that a charge moving through a straight conductor produces a circular magnetic field around the conductor.
- The right-hand rule for a straight conductor states that if a straight conductor is held in your right hand with your right thumb pointing in the direction of the conventional current, your curled fingers will point in the direction of the magnetic field lines.
- Oersted's discovery can be used to produce magnetic fields with properties that can be controlled.

12.2 Questions

1. Copy each diagram in **Figure 7** into your notebook and draw the magnetic field. K/U C

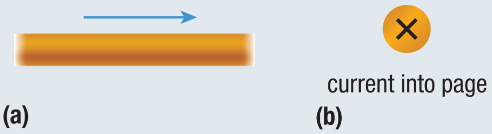


Figure 7

2. Copy each diagram in **Figure 8** into your notebook and label the direction of the conventional current. K/U C

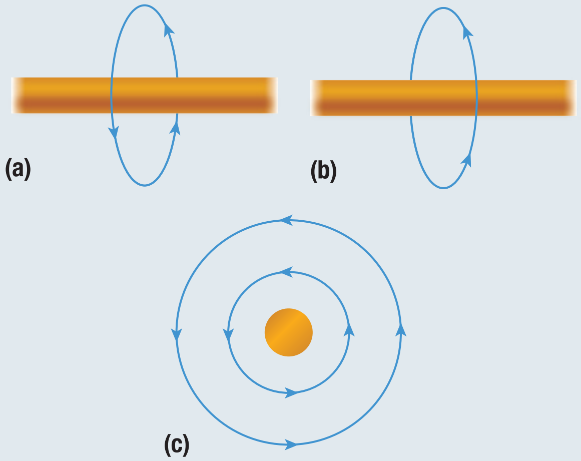


Figure 8

3. A student draws a diagram showing what the magnetic field around a current-carrying conductor looks like. The student draws concentric circles that are equally spaced around the conductor. Explain why the student's diagram is inaccurate. T/I

4. Explain how the diagram in **Figure 9** would change if you were to use the left-hand rule or the right-hand rule. K/U C

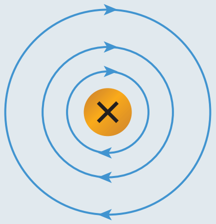


Figure 9

5. You are driving east in your car. Your car is equipped with a magnetic compass display in your rear-view mirror. You happen to drive underneath an electric wire that is labelled high current. You notice that your compass immediately displays north. In which direction is the conventional current flowing in the wire? T/I

6. You use a current-carrying straight conductor to produce a magnetic field. Which three properties of the magnetic field can you control? K/U

7. Which way will the compass point in the diagrams in **Figure 10**? K/U T/I C

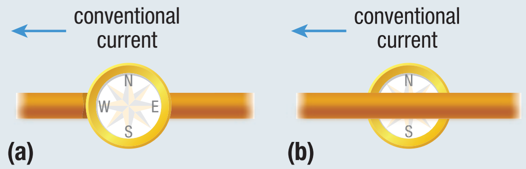


Figure 10

Physics JOURNAL

Wireless Electricity

ABSTRACT

Nikola Tesla imagined being able to transmit electrical energy around the world without wires. He developed a technology called a Tesla coil that was able to do this, but it was unreliable. Today scientists have developed a reliable way to transmit wireless electricity that involves the use of magnetic fields and is aimed at reducing the world's ever-increasing dependence on batteries for portable electronic devices.

Tesla's Vision

Nikola Tesla (**Figure 1**) was an electrical engineer and inventor who was born in 1856 in what is now known as Croatia. He is credited with developing the technology that is at the root of our power systems today—the alternating current generator. Generators transform energy from either renewable or non-renewable sources into electrical energy. You will learn more about generators in Section 13.4.

Early on in the development of an electricity system, much effort was spent in creating networks or "grids" of conducting wires to transmit electrical energy from the power plant to wherever it was needed. It was very expensive to build these grids, and raw materials had to be extracted to make the required parts. Extracting raw materials has environmental consequences, such as destruction of the environment and atmospheric pollution from the machinery. Tesla was interested in finding a way to avoid using electricity grids and dreamed of transmitting electrical energy without wires. He went so far as to say, "Electrical energy can be economically transmitted without wires to any terrestrial distance, I have unmistakably established in numerous observations, experiments and measurements, qualitative and quantitative. These have demonstrated that is practicable to distribute power from a central plant in unlimited amounts, with a loss not exceeding a small fraction of one per cent in the transmission, even to the greatest distance, twelve thousand miles—to the opposite end of the globe."

How did he do it? He used a device called a Tesla coil, which generated electric potential differences as high as one million volts (**Figure 2**). These high electric potential differences caused sparks to fly through the air (arcing) and light fluorescent bulbs tens of metres away. So why are we not using the Tesla coil today? The answer is that the arcing was unpredictable and could not be used reliably.

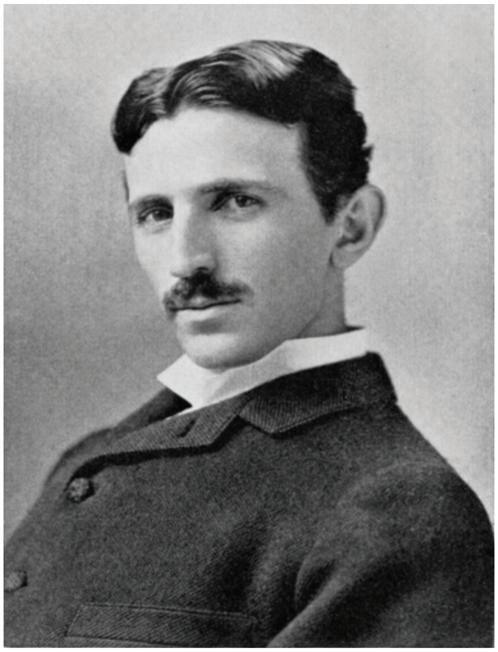


Figure 1 Nikola Tesla developed the alternating current generator.

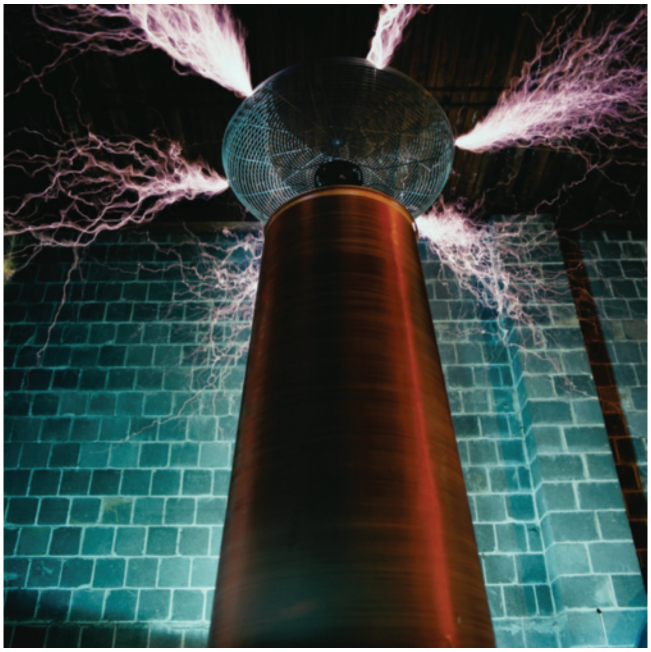


Figure 2 Some of the unpredictable arcing from a Tesla coil

Developments in Portable Electricity

Using wireless electricity to power portable devices was not reliable in Tesla's time, so other available technologies were used. The first batteries were "wet," which means they used a liquid electrolyte. As technology progressed, "dry" batteries were invented that use a paste for the electrolyte. All of these batteries were one-time use only. In 1899, Waldmar Junger invented one of the first rechargeable batteries, called the nickel-cadmium or NiCad battery. In the 1970s the nickel metal hydride or NiMH rechargeable battery was developed to replace the NiCad battery. Shortly thereafter, the lithium ion rechargeable battery was developed. Unfortunately, batteries (whether single-use or rechargeable) ultimately need to be replaced. It is estimated that 15 billion batteries are disposed of every year worldwide, and about 90 % are discarded in landfills. Because of this, there is an environmental concern that the heavy metals in the batteries will leach into the ground water and affect wildlife: cadmium is a carcinogen; mercury is toxic to the brain and liver; and lead can impair intelligence in children. Governments encourage citizens to take their used batteries to recycling centres, but Environment Canada estimates that only 2 % of household batteries are recycled.

Since batteries have their limitations, wireless electricity technology needs to progress. Scientists at the Massachusetts Institute of Technology (MIT) in the United States have picked up where Tesla left off.

Wireless Electricity Today

A team from MIT, headed by Dr. Marin Soljacic, has developed a wireless electricity technology. The electrical energy is transferred from the power source, using magnetic fields, through the air to a capture device. The scientists started by understanding the physics behind magnetically coupled resonators. Resonance allows for the transfer of energy between two objects that have the same natural frequency. The team noted that magnetic fields of two coils of wire that had the same resonant frequency allowed for efficient energy transfer. This property of only transferring energy between the magnetically coupled resonators was important because the energy must not transfer to non-desirable objects such as walls and people. The team narrowed their research to focus on strongly coupled resonators. When strongly coupled, magnetically coupled resonators transfer energy much more efficiently. The shape of the resonators and the distances separating them were found to affect efficiency. The physical theories on how the coupled resonators systems would work were developed and then experimentally verified. The team was able to light a 60 W bulb over a distance of 2.5 m without wires. Their findings were published in the journal *Science* in 2007.

Conclusion

The applications of wireless electricity are staggering because many of the devices we use today are portable and require batteries. This does not mean that batteries will no longer be used, but they may be used less. It suggests that the recharging and use of electronic devices could be done anywhere wireless electricity has been set up. Imagine one day using your electronic device anywhere, without even a plug or a battery.

Futher Reading

Aldrich, L. J. (2005). *Nikola Tesla and the Taming of Electricity*. Greensboro, NC: Morgan Reynolds Publishing, Inc.

Carlson, W. B. (2005). Inventor of dreams. *Scientific American, 292*(3), 78.

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Thompson, K. (2008). Electricity in the air. *Popular Science 272*(2), 62.

GO TO NELSON SCIENCE

12.3 Questions

1. What were some drawbacks of using wireless electricity as suggested by Nikola Tesla? K/U
2. Summarize the environmental concerns about disposable batteries. C A
3. Are you surprised how many (or few) people recycle batteries in Canada? Suggest a reason. C A
4. What are some of the implications of using wireless electricity? A
5. How will wireless electricity affect the use of batteries or adapters that are used for charging at home? A
6. Tesla was very imaginative. His thinking was unconventional and led to new technologies. How do you think Tesla's ideas were perceived by other scientists? How do you suppose Tesla might have been treated because of his novel ideas? C A

Solenoids

12.4

One of the great conveniences in today's motor vehicles is that you can unlock or lock the doors simply by pressing a button on the keys, even from a distance. With older vehicles you have to insert the car key in the door lock. The newer unlocking mechanism works by using the magnetic field of a coiled current-carrying conductor.

Ampère's Experiment

André-Marie Ampère was fascinated by Oersted's discovery, so he decided to investigate other aspects of electricity and magnetism. Ampère took two parallel wires and conducted an experiment to see if the wires would attract or repel one another when opposing currents were sent through them (**Figure 1**).

In Section 12.1, you learned about the properties of magnetic fields. Two magnetic fields can interact with each other to cause a force. The force can either be attractive or repulsive, depending on the directions of the two interacting fields. If two field lines point in the same direction, a repulsion force is applied. Conversely, if two field lines point in opposite directions, an attractive force is applied. Applying the same reasoning to the parallel wires in Ampère's experiment, you can see that the magnetic field lines go in the same direction in between the two wires. This means that the wires should repel each other. Imagine how excited Ampère was when the wires actually did repel.

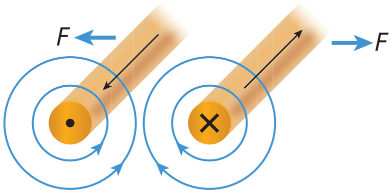


Figure 1 Ampère experimented with two parallel wires with opposing currents. The arrows on the wires show the direction of conventional current.

Coiled Conductors

Now, instead of two parallel wires, let us examine what the magnetic field around a single loop of current-carrying wire looks like. **Figure 2(a)** shows iron filings forming circles around each side of the loop of wire. Note that in the centre of the loop, the magnetic field points straight through. The positive and negative signs on Figure 2(a) denote the direction of the conventional current from positive to negative. A diagram of the magnetic field lines is shown in **Figure 2(b)**.

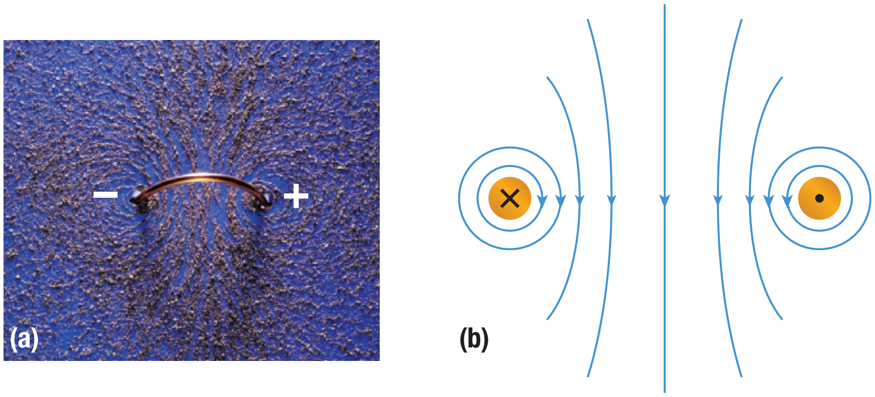


Figure 2 The magnetic field around a loop of wire (a) using iron filings and (b) showing the magnetic field lines

solenoid a coiled conductor

Now imagine winding the conductor into a coil containing several loops. Another name for a coiled conductor is a **solenoid**. The magnetic field around a solenoid has a shape similar to that of a bar magnet. To understand why this is so, look closely at **Figure 3(a)**. The convention of dots and X's is used to show the direction of conventional current. The circular magnetic fields around each dot and X combine to form an overall magnetic field that is a close approximation to the magnetic field of a bar magnet (**Figure 3(b)**). The magnetic field is strongest at the poles or ends of the coils and is weakest at the sides.

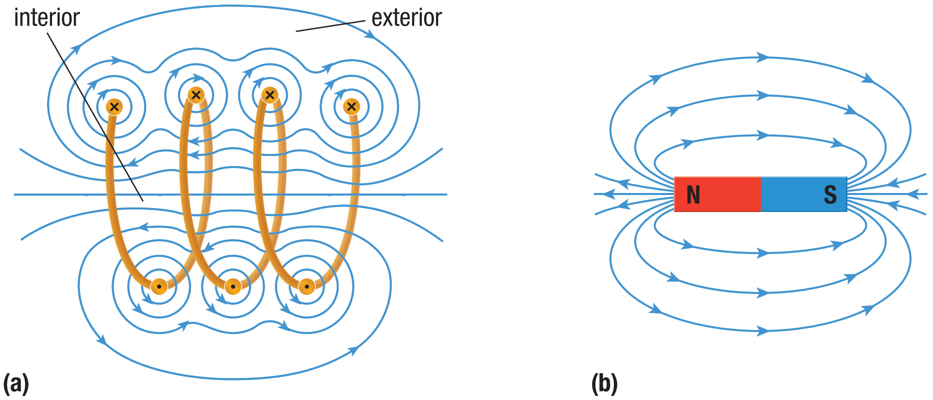


Figure 3 The magnetic field lines around (a) a solenoid and around (b) a bar magnet

electromagnet any device that produces a magnetic field as a result of an electric current

So now we have a way to make an electrically powered bar magnet—an electromagnet. An **electromagnet** is a device that has a magnetic field produced by an electric current. The benefit of the electromagnet is that it can be switched on and off. The strength of the electromagnet can be increased by increasing the number of loops in the coil, increasing the current, or introducing a core made from a material that is quickly magnetized. Soft iron is such a material, and it can be just as quickly de-magnetized when the current is switched off. A core material like soft iron concentrates the magnetic field. To make a very powerful magnet, we include all three factors. The most powerful electromagnets have several thousand loops of wire, work with large currents, and have a soft-iron core.

Right-Hand Rule for a Solenoid

right-hand rule for a solenoid the fingers of your right hand wrap around the coil in the direction of the conventional current, while your right thumb points in the direction of the north magnetic pole of the coil

There is another right-hand rule to help you determine the direction of the magnetic field or the direction of the conventional current. The **right-hand rule for a solenoid** states that if the fingers of your right hand wrap around a coil in the direction of the conventional current, your thumb will point in the direction of the north magnetic pole of the coil (**Figure 4**).

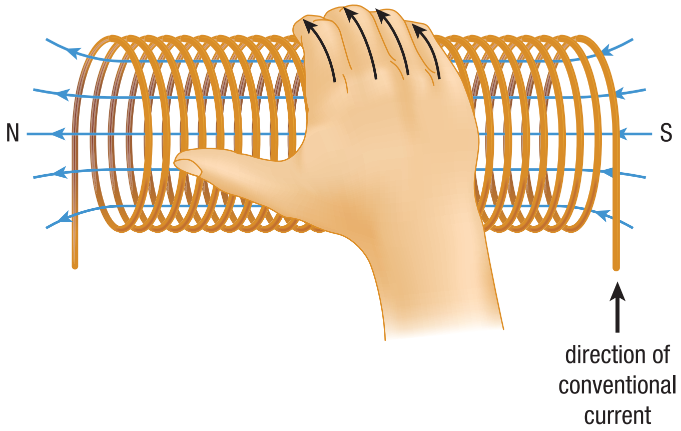


Figure 4 The right-hand rule for a solenoid

LEARNING **TIP**

Right-Hand Rule for a Solenoid
A shorter way to state the right-hand rule for a solenoid is "fingers follow current, thumb points north."

Applications of Solenoids

A solenoid has many uses because it operates like a bar magnet, but it can be switched on and off. So a solenoid can be used to turn things on and off, to pick up things and to then let go, or to cause motion and then reverse the motion. Solenoids are used in many devices, such as audio speakers, electric bells, and cars.

Solenoids in Subwoofers

A subwoofer is a speaker that produces only low-frequency or deep bass sounds. Subwoofer speakers have become popular because they can produce the low-frequency sound effects in surround-sound systems. To produce sound you have to create longitudinal vibrations in the air, with compressions and rarefactions. The subwoofer has a cone made from paper or plastic that quickly moves outward to cause a compression and then quickly moves inward to cause a rarefaction. To move the cone, a permanent circular magnet surrounds a solenoid called the voice coil. The voice coil is connected to the cone. Current is directed through the voice coil by an amplifier, which produces a magnetic field that repels the voice coil and the cone away from the magnet. The amplifier then reverses the direction of the current and produces a magnetic field that attracts the voice coil and the cone toward the magnet. This process repeats continually, producing compressions and rarefactions to create sound (**Figure 5**).

Solenoids in Electric Bells

The school bell signals the beginning or the end of a period. Many schools still have bells based on a solenoid. The design of the electric bell allows it to be rung continuously for as long as needed. **Figure 6** shows the operational parts of an electric bell. When the switch is closed, current is directed to the solenoids. The solenoids produce a magnetic field that is amplified by the soft-iron cores. The soft-iron armature is attracted to the core and the bell rings once. Now the armature pulls away from the contact, so the circuit is interrupted. Since the armature is on a spring, it springs back and makes contact, completing the circuit once more. The process then repeats as long as the switch is closed.

Solenoids in Cars

There are many places in cars where a magnetic field can be used to perform a task. In the starter, a solenoid is used as a switch that completes a circuit to initiate the starter motor, which starts the car. Once the car has started, the solenoid is used to switch off the starter motor because the engine is running. In the door-unlocking mechanism, a solenoid is again used as a switch that completes a circuit to cause an actuator (a device that exerts a force) to unlock the car. Even in a car's automatic transmission, a solenoid is used to initiate gear shifts.

12.4 Summary

- Two parallel wires placed close to one another with opposing currents will repel one another.
- A current in a loop of wire will produce circular magnetic fields around the wire and a straight-line field inside the centre of the loop.
- A current in a coil of wire, or solenoid, will produce a magnetic field that is similar to that of a bar magnet.
- The strength of a solenoid's magnetic field can be increased by increasing the number of loops, increasing the amount of electric current, including a soft-iron core, or any combination of these.
- The right-hand rule for a solenoid is as follows: the fingers of your right hand wrap around the coil in the direction of the conventional current, while your thumb points in the direction of the north magnetic pole of the coil.
- Solenoids are used in many technologies, including subwoofers, electric bells, car starter motors, and car-door locking and unlocking mechanisms.

Investigation 12.4.1

Magnetic Fields around Electromagnets (p. 575)

In this investigation, you will apply what you have learned about solenoids to observe and identify the properties of the magnetic fields around electromagnets.

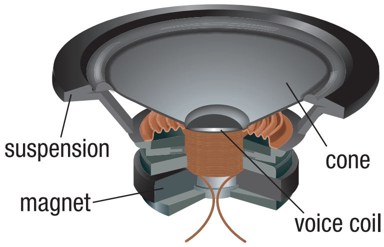


Figure 5 A cross-section of a subwoofer

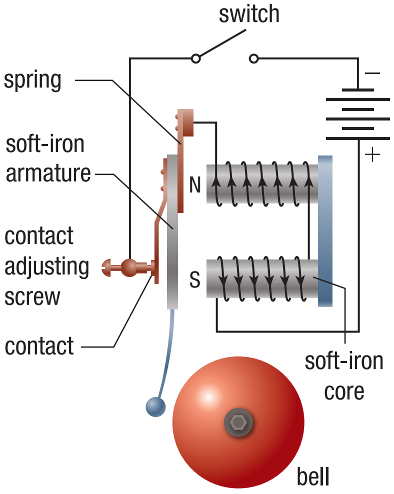
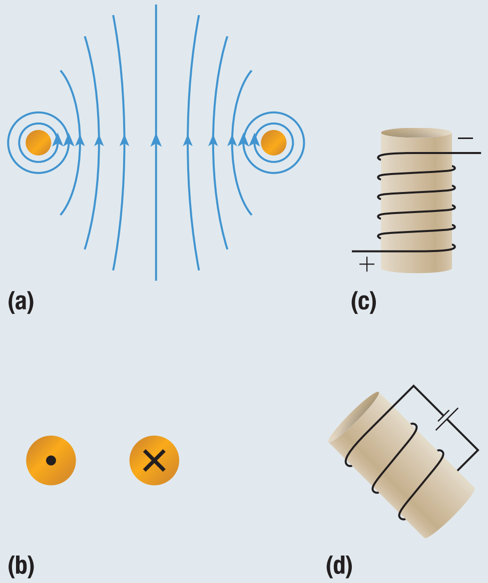


Figure 6 An electric bell

12.4 Questions

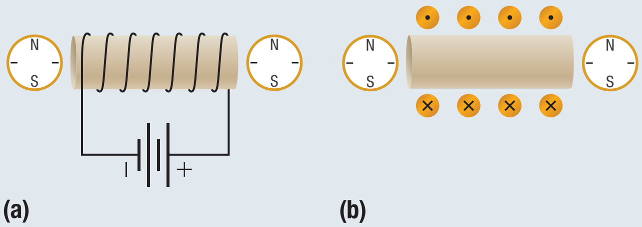
1. Copy the diagrams in **Figure 7** into your notebook, and draw the direction of the conventional current or the magnetic field lines. Also indicate the location of the north and south poles where appropriate. K/U C



(a) (c) (b) (d)

Figure 7

2. Copy the diagrams in **Figure 8** into your notebook, and label the compasses with an arrow pointing in the appropriate direction. K/U C



(a) (b)

Figure 8

3. If two parallel wires are placed beside each other and current is sent down each wire in the same direction, will the wires repel or attract one another? Explain using a diagram that shows the magnetic field lines. T/I C
4. Electromagnet A has 20 loops and a current of 1 A. Electromagnet B has 21 loops and a current of 1.1 A. All other characteristics of electromagnets A and B are the same. T/I
   (a) Which electromagnet is stronger? Explain your choice.
   (b) Would the addition of a soft-iron core to electromagnet A change your answer? Explain.
5. An electromagnetic relay is a device used to trigger another circuit. An illustration of it is shown in **Figure 9**. K/U C
   (a) Describe how it works.
   (b) Describe a situation where an electromagnetic relay may be used.

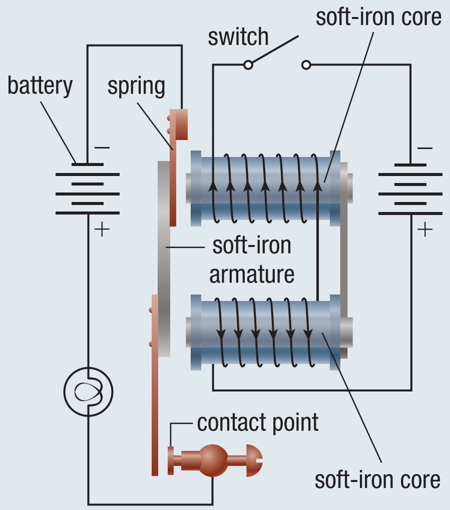


Figure 9

6. Describe how you could adapt an electric bell to become a flashing light. Explain or draw a diagram of your adaptation. C A
7. What factors can be changed to increase or decrease the strength of an electromagnet? Copy **Table 1** into your notebook and complete it. K/U

Table 1 Factors That Can Affect the Strength of an Electromagnet

Factor	An electromagnet can be made stronger by	An electromagnet can be made weaker by

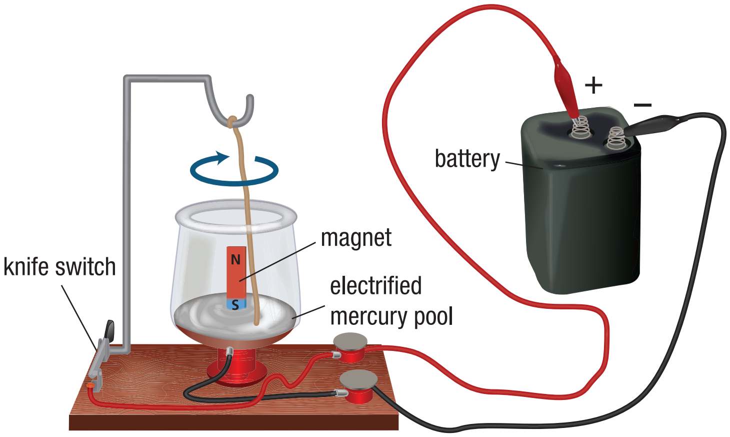
The Motor Principle

12.5

What would life be like without the electric motor? Many devices depend on the electric motor: computers, fans, elevators, car windows, and amusement park rides, to name a few. How did the electric motor come to be?

Moving Conductors with Electricity

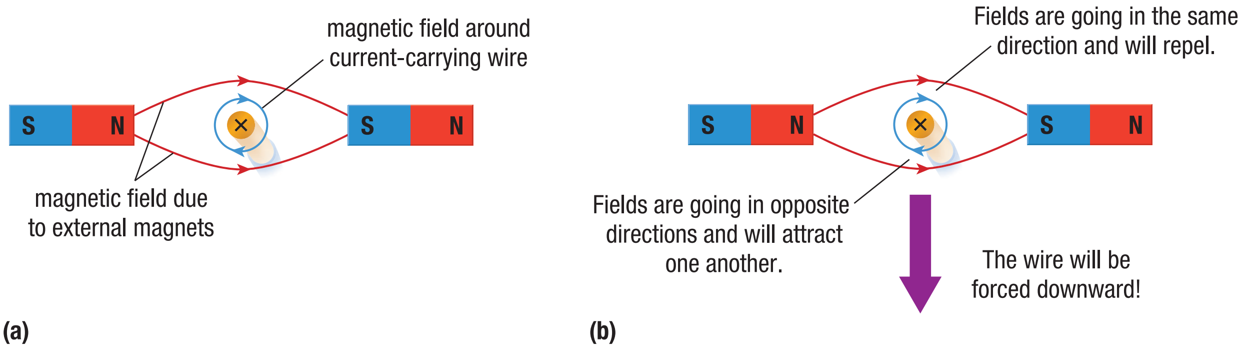
Oersted's discovery inspired much interest in electricity and magnetism among other scientists. When English physicist Michael Faraday saw that an electric current in a wire caused a compass needle to move, he was curious to see if the reverse would be true. Could a magnetic field cause a current-carrying conductor to move? Not only did he succeed in showing that it could, but he was able to make the electrical conductor rotate. In 1821, Faraday supported a bar magnet in a pool of mercury, which is a good conductor of electricity. He then suspended a copper wire alongside the bar magnet, allowing the copper to make contact with the liquid mercury. The wire and the liquid mercury were connected to a power source to complete the circuit. When the circuit was connected, the wire rotated around the magnet. This was the first electric motor (**Figure 1**).



+
–
battery
magnet
N
S
knife switch
electrified
mercury pool

Figure 1 Faraday's motor

The copper wire in Faraday's motor design moved because the magnetic field in the copper wire interacted with the magnetic field of the permanent bar magnet. Let us examine the interaction between the two fields. In **Figure 2(a)** there are two separate magnetic fields. One magnetic field is from a current-carrying conductor with the conventional current directed into the page. The other magnetic field is from the external magnets. Where the two interacting magnetic field lines are pointed in the same direction there is a repulsion force. Where the two interacting field lines are pointed in opposite directions there is an attraction force. The final result is that the conductor is forced downward, as shown in **Figure 2(b)**.



magnetic field around
current-carrying wire
S
N
S
N
magnetic field due
to external magnets
(a)
Fields are going in the same
direction and will repel.
S
N
S
N
Fields are going in opposite
directions and will attract
one another.
The wire will be
forced downward!
(b)

Figure 2 (a) The magnetic field lines around a current-carrying conductor and two permanent magnets (b) The magnetic fields interact to force the conductor in a downward direction.

motor principle a current-carrying conductor that cuts across external magnetic field lines experiences a force perpendicular to both the magnetic field and the direction of the electric current

The movement of a current-carrying conductor in an external magnetic field is described by the motor principle. The **motor principle** states that a current-carrying conductor that cuts across external magnetic field lines experiences a force perpendicular to both the magnetic field and the direction of the electric current. The magnitude of this force depends on the magnitude of both the external field and the current, and the angle between the conductor and the magnetic field it cuts across.

Mini **Investigation**

Moving Wires

Skills: Predicting, Performing, Observing, Analyzing

SKILLS HANDBOOK **A2.1, A2.4**

You will recreate Faraday's experiment using modern equipment.

Equipment and Materials: a DC power supply; a horseshoe magnet; 2 or 3 alligator clip leads

1. Connect the equipment as shown in **Figure 3**.
2. Based on what you have learned about the motor principle, predict which way the wire will move when you turn on the power supply. ✋

✋ Always have your teacher check your circuit. This circuit can produce high currents—turn on the power only briefly.

3. Turn on the power supply and observe any movement. The higher the current, the more noticeable any effect will be. Be sure to hold the insulated part of the lead. You are in effect shorting a power supply, so you should turn on the power only briefly. Turn off the power supply and observe any movement. Repeat if necessary.

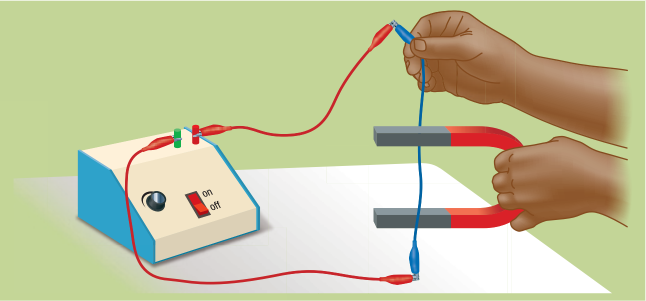


Figure 3 Recreating Faraday's experiment

A. How did your prediction compare to your observation when the power was turned on? T/I C

B. Explain, using the motor principle, why the wire moved in the direction that it did. K/U C

C. Predict which way the wire will move if the horseshoe magnet is flipped over. Test your prediction if your teacher permits you to. K/U T/I C

Right-Hand Rule for the Motor Principle

right-hand rule for the motor principle if the fingers of your open right hand point in the direction of the external magnetic field and your thumb points in the direction of the conventional current, then your palm faces in the direction of the force on the conductor

A third right-hand rule can be used as a tool to determine the direction of force acting on a current-carrying conductor. This time your hand is held flat with your thumb at a right angle to your fingers. The **right-hand rule for the motor principle** states that if the fingers of your open right hand point in the direction of the external magnetic field and your thumb points in the direction of the conventional current, then your palm faces in the direction of the force on the conductor (**Figure 4**).

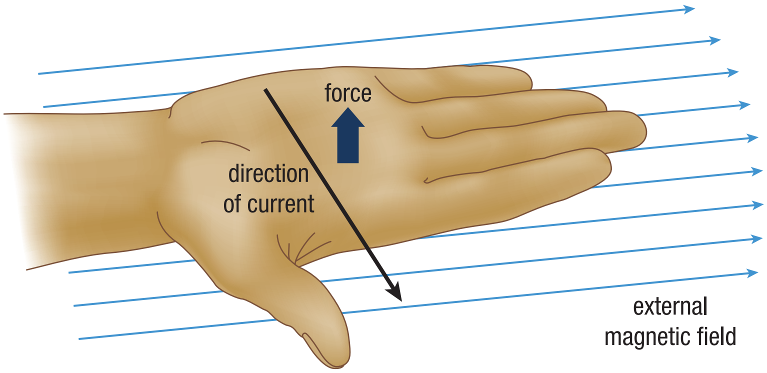


Figure 4 The right-hand rule for the motor principle

LEARNING **TIP**

Right-Hand Rule for the Motor Principle

A shorter way to state the right-hand rule for the motor principle is "thumb points in direction of current, fingers point south, palm faces force."

The Analog Meter

One of the first practical uses of the motor principle was the development of meters for measuring electrical quantities. The motor principle was used to develop the galvanometer—a sensitive meter for measuring current. The first meters were analog. Analog means that the reading is shown using a moving needle or pointer on a scale; there is no digital display. In the analog meter shown in **Figure 5(a)**, you can see the looped conductor where the current enters. Note that the current is directed to the positive terminal, through the loop and then out of the negative terminal. The needle is perpendicular to the coil and fixed to it. The needle and the coil are free to rotate on an axle. The spring provides just the right amount of tension and does not let the needle continue forward. The scale is there to provide a spot to take readings from. Looking at the cross-sectional view in **Figure 5(b)**, you can see the current directed into the page on the right side and out of the page on the left side. Using the right-hand rule for the motor principle, you can see that the loop is forced up on the left side and down on the right side. This causes the needle to rotate toward the right side of the scale. The main advantage of analog meters over digital meters is that it is much easier to see the rate at which changes in readings occur.

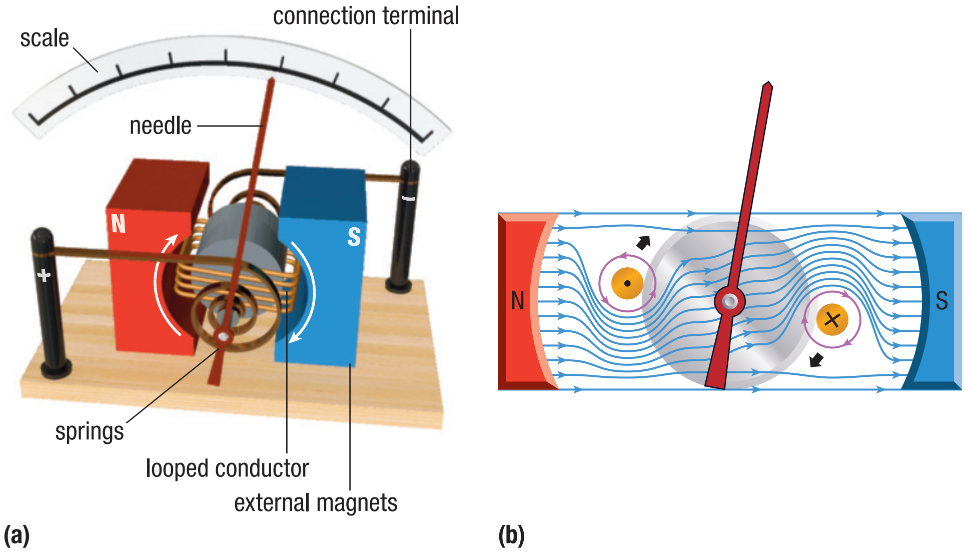


Figure 5 (a) An analog meter and (b) a cross-section of an analog meter

Ammeters

Ammeters measure current in an electric circuit. Ammeters are made from a galvanometer and a resistor. The galvanometer is placed in parallel with a resistor that has a much smaller resistance than the resistance of the galvanometer itself (**Figure 6**). Ammeters are connected in series with the device for which the current is to be measured. When the current is directed to the ammeter, electrons can go through either the galvanometer or the resistor. Since the resistance of the resistor is much smaller, a higher current is directed through the resistor and not the galvanometer. This protects the sensitive coils of wire in the galvanometer's looped coil. The value of the resistor is chosen depending on the range of current that is to be measured.

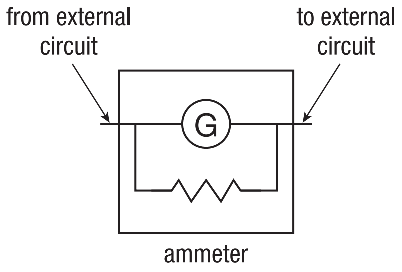


Figure 6 An ammeter with an internal galvanometer

Voltmeters

Voltmeters measure electric potential difference (voltage). Voltmeters are made by placing a galvanometer in series with a resistor with a very high resistance (**Figure 7**). Voltmeters are connected in parallel with the device for which the voltage is to be measured. When the voltmeter is connected to the circuit to measure the voltage,

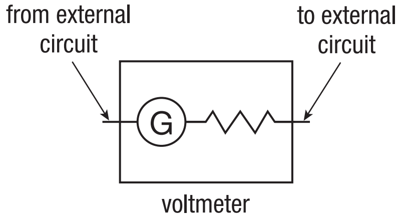


Figure 7 A voltmeter with an internal galvanometer

most of the current is directed into the circuit because of the large resistance in the voltmeter. This protects the galvanometer from large currents.

You may wonder how a galvanometer that measures current is used to measure voltages. Recall from Section 11.7 that Ohm's law describes the relationship between voltage and current. When the galvanometer acts as a voltmeter, the instrument's scale is determined by that relationship, $V = IR$.

12.5 Summary

- An external magnetic field can cause a current-carrying conductor to move.
- The motor principle states that a current-carrying conductor experiences a force perpendicular to both the magnetic field and the direction of the electric current.
- The magnitude of the force on a current-carrying conductor depends on both the magnitude of the external magnetic field and the magnitude of the current.
- The right-hand rule for the motor principle states that if the fingers of your open right hand point in the direction of the external magnetic field and your thumb points in the direction of the conventional current, then your palm faces in the direction of the force on the conductor.
- Analog meters such as the galvanometer, ammeter, and voltmeter operate according to the motor principle.

12.5 Questions

1. Copy each diagram in **Figure 8** into your notebook, and draw the magnetic field lines of both the magnet and the conductor. Then determine the direction of the force on the conductor. T/I C

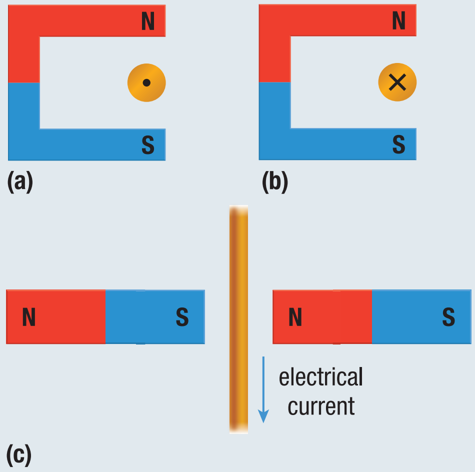


Figure 8

2. What two things can be done to increase the force on a current-carrying conductor according to the motor principle? K/U
3. How would increasing the number of loops in the looped conductor of a galvanometer affect the operation of the galvanometer? K/U
4. (a) Which way will the needle move on a galvanometer if the electron flow model is used?
   (b) Would the needle move in the same direction if the leads connected to the galvanometer were reversed? K/U
5. Suppose that an ammeter is connected in parallel instead of in series to a part of a circuit you wish to measure. What will happen to the amount of current going into the ammeter? T/I
6. A student is repairing a voltmeter by replacing the resistor. The student replaces the resistor with one of a much lower value than the original. What will happen to the amount of current going into the voltmeter when the voltmeter is connected? A

The Direct Current Motor

12.6

When you start up your computer, the fan and the hard drive start to spin. You open the DVD or Blu-ray drive and watch the drawer open. You insert your movie, close the drawer, and wait for the disc to start spinning so the laser can read it and you can watch the movie (**Figure 1**). All of this would be impossible without the modern direct current (DC) motor.

Figure 1 Watching a DVD on a laptop is possible because of a DC motor.

Getting Motion to Occur Continuously

In the Mini Investigation in Section 12.5, you produced motion in a wire using a magnetic field. But the motion will only occur once. What if you want the motion to be continuous? Looking back at the galvanometer design, it is possible to get part of a complete turn, but the spring prevents further motion. Furthermore, the loop and the needle are forced back in the opposite direction once the coiled conductor has rotated past the halfway point. Scientists wanted to find a way to temporarily interrupt the current and then change its direction, and thus the direction of the magnetic field.

One simple but ingenious idea was to create a device called a split ring commutator. The commutator is split so that the circuit is incomplete when the loop is aligned with the split. In **Figure 2**, the wire loop is connected to a split ring commutator. The split ring commutator and the wire loop are free to rotate around an axis. The brushes are made out of conducting bristles. They make contact with the split ring commutator but still allow rotation. The rotor is the part of the motor that rotates and the stator is the part of the motor that remains stationary. In Figure 2, the loop is the rotor and the external magnets are the stator.

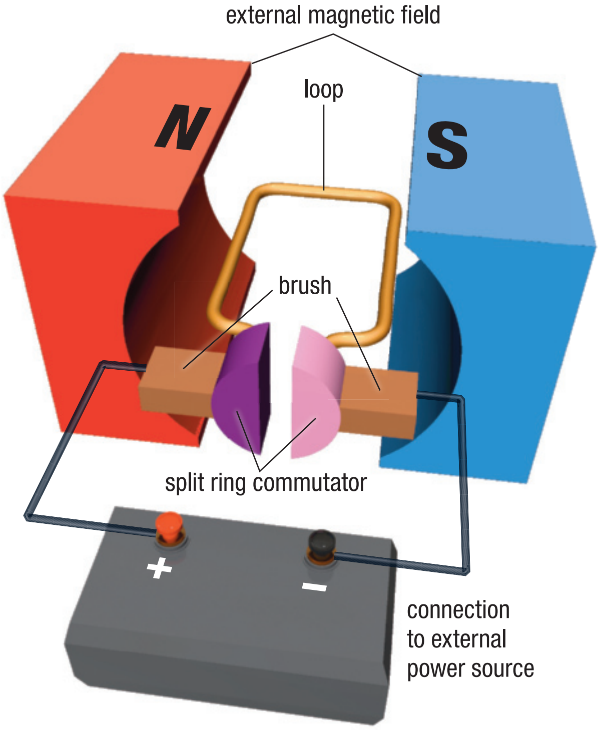


Figure 2 The parts of a DC motor

A DC motor uses an electric current in a conductor which generates a magnetic field that interacts with an external magnetic field to cause rotation. In the following Tutorial, we will go through the step-by-step process of how the DC motor spins and how the right-hand rule for the motor principle is applied.

Tutorial **1** The DC Motor

These four diagrams show the step-by-step process of how a DC motor turns.

In **Figure 3**, a conventional current is directed from the positive terminal toward the brushes, making contact with the purple part of the split ring commutator. Charges flow into the left of the loop and exit from the right into the pink part of the split ring commutator to the brush and back to the negative terminal. Using the right-hand rule for the motor principle, we see that the force is downward at the left of the loop and upward at the right of the loop. This will start a counterclockwise rotation.

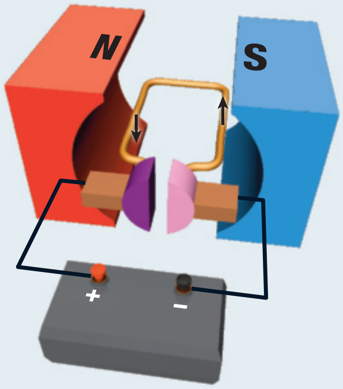


Figure 3

In **Figure 4**, the motor rotates counterclockwise, and the situation is the same as it was in the first step. The current is directed to the purple split ring of the commutator, and charges flow into the left of the loop and exit from the right of the loop. The forces are still in the same direction, as predicted by the right-hand rule.

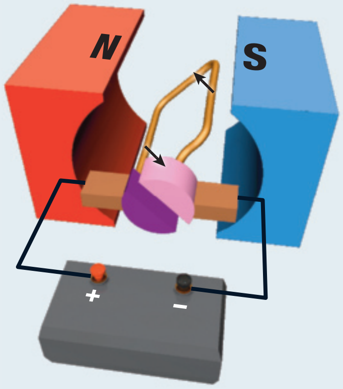


Figure 4

In **Figure 5**, the wire loop has rotated to the split. The circuit is now open, there is no current, and no more magnetic fields are being produced by the loop of wire. The loop will continue to spin due to inertia.

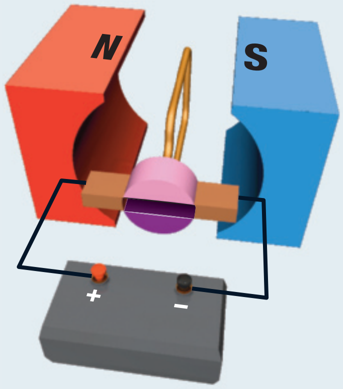


Figure 5

In **Figure 6**, the electric current is now directed into the pink part of the split ring commutator. This directs the current into the left of the loop once again and out of the purple part of the split ring to the brush and to the negative terminal. Using the right-hand rule, you can see that the right of the loop is being forced upward while the left of the loop is being forced downward. So the counterclockwise rotation continues.

The rotation of the loop continues counterclockwise until it again reaches the split in the split ring commutator. This will once again interrupt the current until contact is made from the positive terminal to the purple part of the split ring commutator. The process will start over.

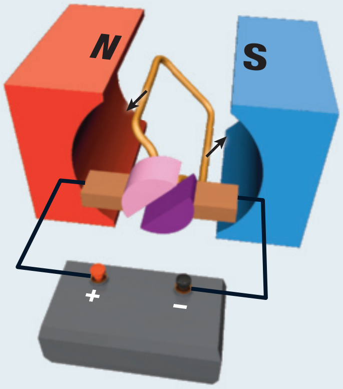


Figure 6

Improving the Design

The design of the DC motor shown in Tutorial 1 has some shortcomings. A motor with just one loop will not be very strong. To improve the strength of the magnetic field in the loop, you can increase the number of loops, increase the current, or include a soft-iron core. Increasing the current is not a desirable choice because it will produce more thermal energy as a side effect. So designers increase the number of loops and include a soft-iron core called an armature. In Tutorial 2, we will go through the step-by-step process of how a DC motor with an armature spins.

Investigation **12.6.1**

Building and Investigating a Prototype Motor (p. 576)

In this investigation you will use what you have learned about DC motors to build a prototype motor and investigate its properties.

Tutorial 2 The Armature DC Motor

The next three figures show the step-by-step operation of a DC motor with an armature.

In **Figure 7**, the current is directed into split ring B. As a result, the charges go up the coil at the front of the coil and then exit from split ring A. Instead of using the right-hand rule for the motor principle, use the right-hand rule for a coil. Your fingers go up the coil following the conventional current and your right thumb points left, indicating that the left side of the coil is a north magnetic pole. The north pole from the external magnet and the north pole from the armature repel one another and cause a clockwise rotation. A similar thing happens with the two south magnetic poles.

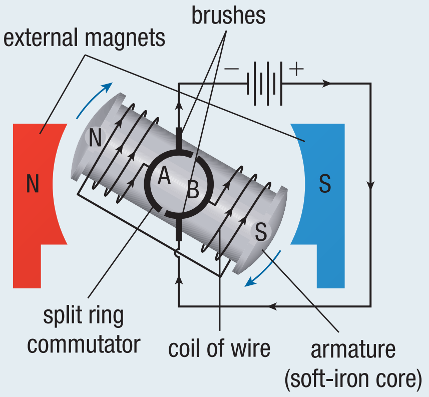


Figure 7

In **Figure 8**, the current is still directed into split ring B and the situation is the same. The clockwise rotation continues. Note that the north pole of the armature is attracted by the south pole of the external magnets. In the previous step, clockwise rotation occurred because of magnetic repulsion. Now clockwise rotation continues because of magnetic attraction.

The armature rotates until it reaches the split. Now the circuit is interrupted and there is no current. The armature continues to spin due to its inertia.

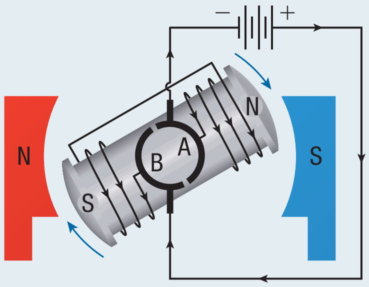


Figure 8

In **Figure 9**, the current is now directed into split ring A. The charges go up the front of the coil and exit at split ring B. Using the right-hand rule for a coil, you can see that the left side of the armature is a north pole again. The north pole on the armature repels the north pole on the external magnets, and clockwise rotation continues. If the split did not occur, the left side of the armature would be a south magnetic pole and would be attracted back toward the external magnet north pole, stopping the rotation of the motor. Due to the split, the magnetic poles of the coil change and the coil continues to rotate.

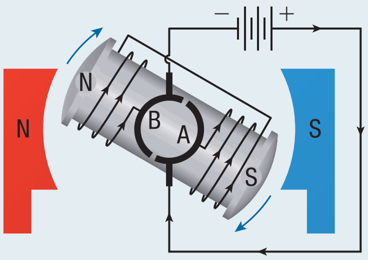


Figure 9

Mini **Investigation**

Observing a DC Motor

Skills: Performing, Observing

SKILLS HANDBOOK A2.1

Now that you have learned about the DC motor, you should be able to identify the parts of a DC hobby motor (**Figure 10**).

TYPE
VOLTS
R.P.M.
SERIAL NO.
D.C.
LONDON. W.3. ENGL
EQUIPMENT
+

Figure 10

Equipment and Materials: DC hobby motor

1. Following your teacher's instructions, carefully disassemble a hobby motor.
2. Carefully examine each part of the motor and write a list of parts that you recognize and their function.

A. How many parts did you recognize? Are there any parts that you did not recognize? Record your answers in a t-chart. K/U T/I C

B. Did the design of the hobby motor look like the designs that you have studied so far? Explain. K/U T/I C

C. What parts were different in design from what you have studied so far? Give details about the differences. K/U T/I

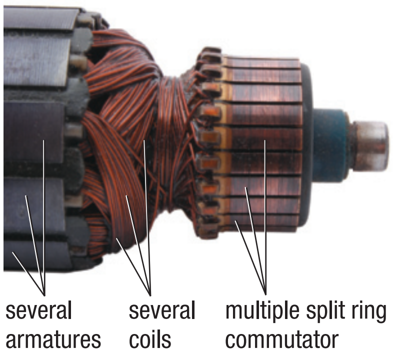


Figure 11 A DC motor with multiple split rings

Further Improvements in Motor Design

The armature design greatly improves the power of an electric motor. However, the magnetic force is strongest in the coil when it is lined up with the magnetic fields of the external magnets. As the coil rotates away from being lined up with the external magnetic field, the strength of the magnetic force on the coil weakens and the motor slows down. Another problem is that if the motor is turned off just as it reaches the split in the split ring commutator, then it will not be able to rotate when the motor is turned on again because the circuit is incomplete. You would have to give the motor a push.

To overcome these issues, DC motor designers put several coils into the motors and use a split ring commutator with several splits (**Figure 11**).This means that the speed of the motor does not fluctuate as much and a segment of the multiple split ring commutator is always in contact with the external circuit. The motor does not need to be pushed by hand to start it.

Applications of Motors

Electric motors are all around you and many mechanical movements you see are caused by an electric motor. They can be found, for example, in household appliances, cars, and trains. They are used to apply forces (for example, power tools), for cooling (for example, in laptop computer fans), as starters (for example, in cars), or to move things (for example, to spin a DVD).

Some cars now rely on electric motors for propulsion. Hybrid cars use an electric motor alongside a gasoline engine. The electric motor runs on battery power which reduces pollution from the gasoline engine. Once the battery runs low, the electric motor can no longer propel the vehicle. The car then runs on its gasoline engine and at the same time charges the battery. Some vehicle manufacturers have developed completely electric vehicles. While electric vehicles have the potential to be environmentally friendly, it does depend on how the electricity used to charge the battery is generated. Motors also contain heavy metals, which can be toxic to living things. Care must be taken to properly discard motors once they are no longer functioning.

Research This

Brushless Motors

Skills: Researching, Communicating SKILLS HANDBOOK A5.1

The motor designs you have studied are still in use after many years because they are reliable and economical. However, the brushes in these designs make contact with the split rings and can wear out. Also, brush designs often produce small sparks as the brushes go past the splits. There is a design that does not use brushes.

1. Research brushless motor designs and their applications.

A. Create a t-chart comparing the designs of brushless motors to brush-type motors. T/I C

B. Explain how brushless motors work, and identify the stator and rotor. T/I C

C. What advantages do microprocessor-controlled brushless motors have? T/I C A

D. List some applications of brushless motors. C A

GO TO NELSON SCIENCE

12.6 Summary

- The split ring commutator is the part of a DC motor that interrupts the circuit. It changes the direction of the current and the direction of the magnetic field, keeping the motor spinning continuously.
- A DC electric motor consists of a rotor and a stator.
- A DC electric motor uses an electric current to produce a magnetic field in a coil. The coil starts to rotate in an external magnetic field.
- Brushes make physical contact with the split ring commutator to complete the circuit and still allow rotation.
- Using a soft-iron armature and increasing the number of loops in the coil will increase the strength of the motor.
- Using several split rings and coils prevents the need to manually start a motor.
- Motors are used in many electrical devices.

UNIT TASK **BOOKMARK**

You can use what you have learned about the design of DC motors as you work on the Unit Task on page 622.

12.6 Questions

1. (a) Identify the parts labelled A, B, C, D, E, and F for the motor shown in **Figure 12**.
   (b) Determine which way the motor will spin. Explain your answer.
   (c) What effect will reversing the current have? K/U T/I C

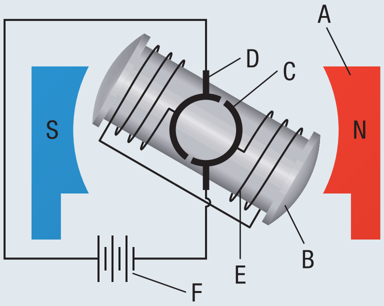


Figure 12

2. (a) Look at **Figure 13**. In which direction will the loop rotate? Explain your answer.
   (b) What is the purpose of the split ring commutator? K/U T/I C

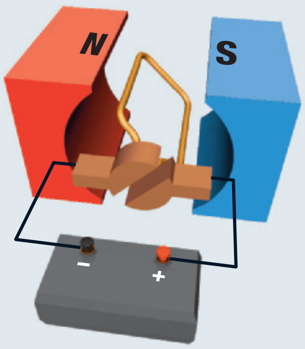


Figure 13

3. What effect would each of the following changes have on a DC motor? Consider each of the changes separately. K/U
   (a) increasing the number of loops in the coil
   (b) using a plastic core instead of a soft-iron core
   (c) decreasing the current
   (d) reversing the polarity of the external magnets
   (e) reversing the polarity of the external magnets and reversing the direction of the current

12.7 Explore Applications in Electromagnetism

SKILLS MENU

- Researching
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating
- Identifying Alternatives

Magnetic Resonance Imaging

Medical diagnostic imaging technologies are an important part of our healthcare system. They provide information that can aid in the detection and treatment of illnesses. These technologies include X-rays, ultrasound, and magnetic resonance imaging (MRI).

X-rays provide good pictures of the bones in your body but cannot take pictures of soft tissue effectively. They are also potentially harmful if done too often or if taken during pregnancy. Ultrasound provides good pictures of soft tissue but cannot penetrate bone. MRI technology has the benefit of being able to show both bone and soft tissue in very good detail (**Figure 1**).

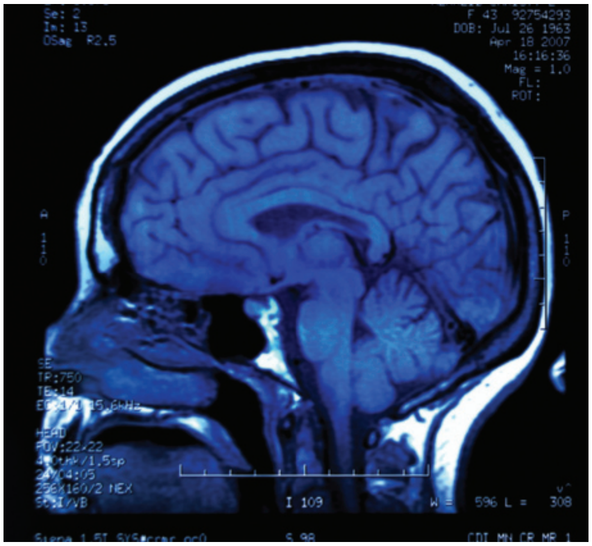


Figure 1 An MRI scan of a brain

The drawbacks of magnetic resonance imaging are that the machines are very expensive, are noisy, and cannot be used in certain situations. The MRI machine cannot be used if the patient is claustrophobic (afraid of confined spaces), has a heart pacemaker (pacemakers will not function properly in the strong magnetic field), or has metal implants (the magnetic field can exert a great force on the implant, causing harm).

In Canada, the number of MRI scanners varies by province. Some provinces, such as Ontario and Quebec, have many, while other provinces, such as Newfoundland and Labrador and Saskatchewan, have fewer. Long wait times are common across the country, with some patients waiting months or even up to a year for access to an MRI. Private MRI clinics are available in Canada and can often offer immediate access to an MRI. However, these clinics are not covered by provincial health care, so the cost of the MRI scan must be covered by the patient.

CAREER **LINK**

An MRI technician helps patients understand the technology and is often the person who operates the MRI scanner. To find out more,

GO TO NELSON SCIENCE

The Application

Your friend has a sports-related injury and the doctor has requested an MRI scan to diagnose the injury and plan a course of treatment. Your friend has never had an MRI scan and is a little apprehensive about it. You decide to help your friend become more informed about MRI technology and to document the experience.

Your Goal

To research MRI technology and its use in Canada

Research

SKILLS HANDBOOK A5.1

Use library or Internet resources to research information on MRI technology. You may also choose to interview people who have experience with MRI technology: a doctor who refers patients for MRI scans, an MRI technician, or a patient who has undergone an MRI scan.

Some research topics include

- how MRI works, and its advantages and drawbacks
- advances in MRI technology
- what an MRI experience entails
- average wait times for MRI scans across Canada
- cost of an MRI scan
- cost of an MRI scanner
- training needed to become an MRI technician
- number and distribution of publicly funded MRI scanners across Canada
- number and distribution of private MRI clinics across Canada

WEB LINK

To find out more about MRIs,

GO TO NELSON SCIENCE

Summarize

Organize your research under topics that will provide useful information for your friend. Some questions you may want to consider are

- How does an MRI work?
- What does an MRI scan feel like?
- How long will your friend have to wait for an MRI scan in your community?
- How long would they wait in other areas of the country? Do you think this is fair?
- Are there private MRI clinics in your community? How long would your friend have to wait for a private MRI scan? How much would the MRI scan cost?

Communicate

Write a report for your school newspaper summarizing your research and relating it to the MRI experience of your friend. Your article should be written so that it presents information about MRI as well as about the experience of receiving an MRI scan. Your article should close with a conclusion on the advantages and disadvantages of receiving an MRI scan.

CHAPTER 12 Investigations

Investigation 12.1.1 OBSERVATIONAL STUDY

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Properties of Magnetic Fields

Magnetic fields are invisible regions of influence that affect magnetic substances. Compass needles are also affected and line up with magnetic field lines. In this investigation you will use iron filings and compasses to investigate magnetic fields.

Purpose

To identify the properties of magnetic fields around permanent magnets

Equipment and Materials

- eye protection
- 4 mini compasses
- bar magnet
- horseshoe magnet
- circular (or button) magnet
- magnetic dip needle
- magnetic field sensor (if available)
- sheet of acetate
- iron filings

Procedure

1. Using a mini compass, determine the direction of Earth's magnetic north pole.
2. Place a sheet of acetate over the bar magnet. Carefully sprinkle some iron filings onto the acetate directly over the poles of the magnet and then around the perimeter. Record your observations in a diagram.
3. Carefully remove the acetate from the bar magnet and collect the iron filings by pouring them into the iron filings container.
4. Place 4 mini compasses around the bar magnet, one at each side and one at each end. Record your observations of the poles of the magnet and the directions of the compasses in a diagram. If a magnetic field sensor is available, you can use it in place of the compasses.
5. Repeat Steps 2–4 with the horseshoe magnet and the circular magnet. Place the compasses (or magnetic field sensor) at four different points around each magnet.
6. Using the magnetic dip needle, measure the inclination of Earth's magnetic field. Record the measurement as an angle in degrees.

Analyze and Evaluate

(a) The distribution of the iron filings is related to the strength of the magnetic field. Where is the magnetic field the strongest, and what happens to the field as you move farther away from the magnet? T/I

(b) The mini compasses map out the direction of the magnetic field. From which pole does the magnetic field exit the bar magnet? T/I

(c) At which pole does the magnetic field enter the bar magnet? T/I

(d) How does the direction of the compass needles at the sides of the bar magnet compare to that of the compasses at the poles of the bar magnet? T/I

(e) What does the magnetic field around a horseshoe magnet look like? Do the magnetic fields enter and exit as they did in a bar magnet? T/I C

(f) What is the shape of the magnetic field around the circular magnet? T/I C

(g) What is the dip angle of Earth at your location? Draw a diagram of Earth's magnetic field based on your observations. T/I C

Apply and Extend

(h) What would happen if a horseshoe magnet interacted with a bar magnet? Predict by drawing a diagram of the directions of the magnetic fields. Use the mini compasses to check your prediction. T/I C A

(i) If a compass aligns with the magnetic field of Earth, what magnetic pole must Earth's north magnetic pole actually be? Explain your reasoning. T/I

(j) If two bar magnets are placed so that the north and south poles are facing each other, in which direction will a compass needle point if placed directly between the poles? T/I

Investigation 12.4.1 OBSERVATIONAL STUDY

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Magnetic Fields around Electromagnets

Electromagnets are made from an electrical conductor with a current flowing through it. As soon as the current is sent into the conductor, a magnetic field is produced and the conductor becomes an electromagnet. What do the magnetic fields around electromagnets look like?

Purpose

To identify the properties of magnetic fields around electromagnets

Equipment and Materials

- straight conductor
- ammeter
- 4 alligator clip leads
- variable DC power supply
- 4–6 mini compasses
- coiled conductor
- magnetic field sensor (if available)

In this experiment, you are effectively shorting the variable DC power supply. To avoid overloading the power supply, leave it on for short periods of time only and do not turn the current up quickly. Always start at a low setting and turn it up slowly until a change in the compass direction is noted. Never touch any part of the circuit while it is connected to the DC supply.

Procedure

SKILLS HANDBOOK A3

Part A: Straight Conductor

In this part of the observational study, you will identify the magnetic fields around a straight conductor with a current going through it.

1. Set up a circuit that has a straight conductor connected to the ammeter in series with the variable DC power supply.
2. Hold the straight conductor horizontally 1 cm above the lab bench. Orient the conductor so that it is aligned with north and south. Use a compass to help. Place the compass directly underneath the conductor.
3. Slowly turn up the power supply until you notice the compass change direction. Record your observations in a diagram and note the current on your ammeter.
4. Turn off the power supply. Now place the compass on top of the conductor. You may need to hold it in place.
5. Slowly turn up the power until you notice the compass change direction. Record your observations in a diagram.
6. Turn off the power supply. Suspend the conductor vertically.
7. Slowly turn up the power and, using a compass, map the direction of the magnetic field close to the conductor in a horizontal plane 360° around the conductor. Record your observations in a diagram. Note the current on your ammeter.
8. Slowly move the compass farther away from the conductor. Record your observations.
9. Turn off the power and disassemble your circuit.

Part B: Coiled Conductor

In this part of the observational study, you will identify the magnetic fields around a coiled conductor with a current going through it.

10. Set up a circuit that has a coiled conductor connected to the ammeter in series with the variable DC power supply.
11. Place 4–6 mini compasses around the coiled conductor. Be sure to put one at each opening of the coil.
12. Slowly turn up the power until you notice a change in the directions of the compasses. Record your observations in a diagram. Note the current on your ammeter.
13. Quickly turn off the power supply and record the directions of the compasses in a diagram.
14. Slowly turn up the power until you again note a change in the directions of the compasses. Move the compasses away from the coil until you notice a change. Turn up the power until you notice a change in the compasses. Note the current on the ammeter.
15. Turn off the power supply and disassemble your circuit.

Analyze and Evaluate

(a) How did the compass directions compare in Steps 3 and 5? T/I

(b) What shape of magnetic field is formed around the conductor in Step 7? K/U

(c) Was there a difference in the amount of current required to notice a change in the compass directions in Steps 3 and 7? K/U

(d) What happened when you moved the compass farther away from the conductor in Step 8? K/U

(e) How much current was required to produce a change in the compass directions in Step 12? K/U

(f) How does the shape of the magnetic field of the coil compare to the magnetic field around a bar magnet? T/I

(g) What happened when you turned the power off quickly in Step 13? K/U

(h) What effect did increasing the current in Step 14 have on the strength of the magnetic field at a distance farther away from the coil? K/U

Apply and Extend

(i) What effect would changing the number of loops in the coil have on the amount of current needed to produce a change in the direction of the compasses? A

(j) Electromagnets can be used in cranes to lift metal parts. The parts can be moved to the desired location, the magnetic field can be turned off, and the metal parts dropped. Based on your observations in this lab, suggest a possible way to lift heavier metal parts. A

Investigation 12.6.1 CONTROLLED EXPERIMENT

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Building and Investigating a Prototype Motor

In this activity, you will build a prototype DC motor. The motor has all the parts you learned about in Section 12.6 and is based on the loop design. It does not have an armature.

Testable Question

How does the number of loops in a coil affect the rotation speed of the motor?

Hypothesis

Make a hypothesis about how the number of loops in the coil of a motor will affect its speed of rotation. Include a reason for your hypothesis.

Variables

Read the Testable Question, Experimental Design, and Procedure. Identify the controlled, manipulated, and responding variables in this experiment.

Experimental Design

You will build a motor with a partner (**Figure 1**). Each pair of students will build a motor with a different number of loops in the coil, so that no two motors have the same number of loops. The current going into the coil, the size of the cork, and the strength of the external magnetic field will be the same for each motor. You will measure the speed of rotation of your motor.

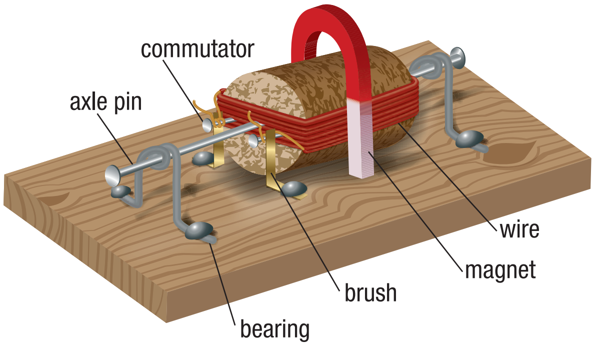


Figure 1 A DC cork motor

Equipment and Materials

- ammeter
- variable DC power supply
- horseshoe magnet
- 3 alligator clip leads
- cork
- 2 short pins and 2 long pins
- insulated wire to wrap around the cork
- 2 paper clips
- 6 thumbtacks
- wooden base
- 2 copper strips
- strobe light to measure speed of rotation

Strobe lights can cause unpleasant physiological effects. Inform your teacher if you have a medical condition such as epilepsy, or if you become ill while operating the strobe light.

Procedure

1. Read Section 12.6 to review how a DC motor works. Make sure you know what is meant by "commutator" and "brushes."
2. Carefully place a long pin into the centre of each end of the cork (Figure 1).
3. Place the two short pins on one end of the cork, as shown in Figure 1, for your commutator.
4. Determine how much wire you need to make the loops that you will wind around the cork. Then have your teacher bare the ends of the wire.
5. Wrap one bare end of the wire around a commutator pin. Then wrap the loops around the cork the number of times assigned to your group by your teacher. Wrap the other bare end to the other commutator pin.
6. Build bearings out of bent paper clips, as shown in Figure 1. Mount the bearings on the wooden base using the thumbtacks.
7. Make brushes out of copper strips and attach them using thumbtacks into the wooden base.
8. Mount the horseshoe magnet around the cork. If a horseshoe magnet is not available, you may use bar magnets, but opposite poles must be on either side of the cork.
9. Connect alligator clip leads to the power supply with an ammeter in series with the brushes.
10. Turn on the power supply and adjust until the current reads 1.0 A on the ammeter.

Never touch any part of the circuit while it is connected to the DC power supply.

11. With the help of your teacher, measure the speed of the motor using a strobe light.

Observations

Record the number of loops and the rotation speed of the motor in an appropriate chart. Canvass other groups and share the data so that you can present the data from the whole class.

Analyze and Evaluate

(a) Was your hypothesis correct? What evidence do you have to support your answer? T/I

(b) What variables were measured and what variable was manipulated? What is the independent variable? What is the dependent variable? T/I

(c) Plot a graph of the rotation speed of a motor versus the number of loops in the coil. C

(d) What type of relationship did you find from your graph? Was the relationship linear or non-linear? T/I

(e) What was the proportionality between the data? Was it directly proportional or inversely proportional? T/I

(f) If rotation speed is given the symbol R and number of loops is given the symbol N, write a proportionality statement. T/I

(g) Using the same symbols as in question (f), write an equation. T/I

(h) Identify one source of error. T/I

(i) Answer the Testable Question. T/I

Apply and Extend

(j) What effect would not keeping the length of the wire constant have on the results? A

(k) Suggest another controlled investigation that could have been done with this motor. A

CHAPTER 12 SUMMARY

Summary Questions

1. Create a study guide based on the points listed in the margin on page 546. For each point, create three or four sub-points that provide further information, relevant examples, or explanatory diagrams.
2. Look back at the Starting Points questions on page 546. Answer these questions using what you have learned in this chapter. Compare your latest answers with those that you wrote at the beginning of the chapter. Note how your answers have changed.

Vocabulary

magnetic field (p. 548)

Oersted's principle (p. 553)

right-hand rule for a straight conductor (p. 554)

solenoid (p. 560)

electromagnet (p. 560)

right-hand rule for a solenoid (p. 560)

motor principle (p. 564)

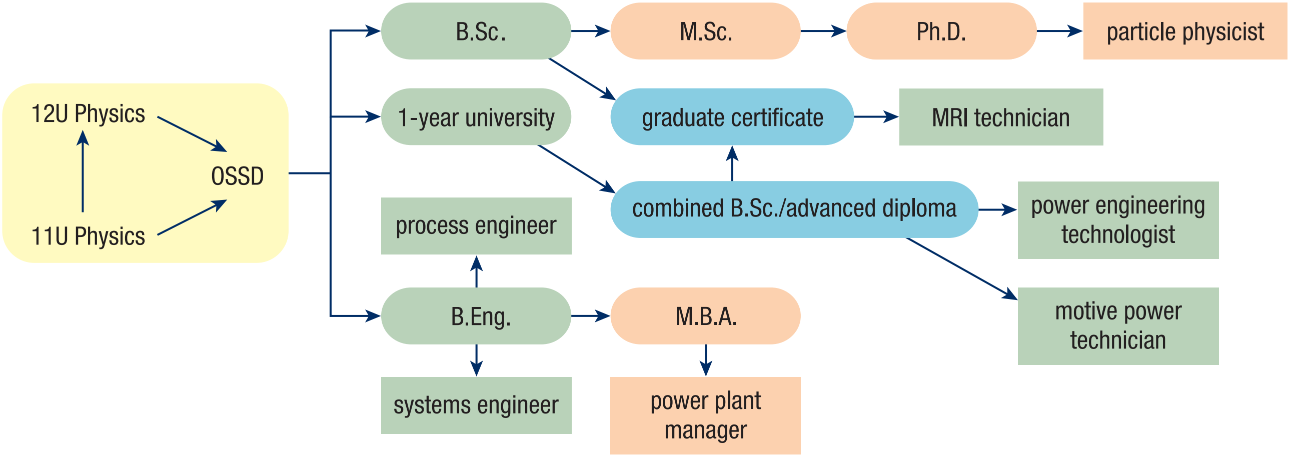
right-hand rule for the motor principle (p. 564)

CAREER PATHWAYS

SKILLS HANDBOOK A7

Grade 11 Physics can lead to a wide range of careers. Some require a college diploma or a bachelor of science degree. Others require specialized or postgraduate degrees. This graphic organizer shows a few pathways to careers related to topics covered in this chapter.

1. Select an interesting career that relates to Electromagnetism. Research the educational pathway you would need to follow to pursue this career.
2. What is involved in the program to become a power engineering technologist? Research at least two programs, and prepare a brief report of your findings.



12U Physics
11U Physics
OSSD
B.Sc.
M.Sc.
Ph.D.
particle physicist
1-year university
graduate certificate
MRI technician
process engineer
combined B.Sc./advanced diploma
power engineering technologist
B.Eng.
M.B.A.
motive power technician
systems engineer
power plant manager

GO TO NELSON SCIENCE

CHAPTER 12 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. Which of the following is a region of space surrounding an object that causes another object to experience a force? (12.1) K/U
   (a) vector
   (b) field
   (c) moment
   (d) range
2. Which of these fields exist in nature? (12.1) K/U
   (a) electric fields
   (b) magnetic fields
   (c) gravitational fields
   (d) all of the above
3. Magnetic field lines
   (a) have equal spacing regardless of distance
   (b) can be mapped using a compass
   (c) exist in two dimensions only
   (d) are visible to the naked eye (12.1) K/U
4. Maglev trains use magnets to reduce the effect of
   (a) propulsion
   (b) crosswinds
   (c) friction
   (d) momentum (12.1) K/U
5. Which direction does a compass point when it is near to a wire conducting electricity? (12.2) K/U
   (a) north
   (b) directly toward the wire
   (c) directly away from the wire
   (d) none of the above
6. Oersted theorized that magnetic fields
   (a) are not produced by an electric current in a wire
   (b) are circular around an electric current in a wire
   (c) are attracted to an electric current in a wire
   (d) are parallel to an electric current in a wire (12.2) K/U
7. What is one benefit of a solenoid over a bar magnet? (12.4) K/U
   (a) A bar magnet can be turned on and off.
   (b) A solenoid's magnetic field can be reversed.
   (c) Solenoids are found in nature.
   (d) all of the above
8. The fingers of your right hand are wrapped around a current-carrying solenoid. Your right thumb is at a 90° angle to your fingers and is pointing right. What is the direction of the current in the solenoid? (12.4) K/U
   (a) down the front of the coil
   (b) left at the front of the coil
   (c) right at the front of the coil
   (d) up the front of the coil
9. A current is directed eastward through a wire located in a magnetic field pointing north. In which direction will the wire be forced? (12.5) K/U
   (a) south
   (b) west
   (c) upward
   (d) downward
10. Which of these allowed the technological advance from analog meters to DC motors? (12.6) K/U
   (a) looped wires
   (b) split ring commutators
   (c) external magnets
   (d) ammeters

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

11. A magnetic field exists around a magnet only when it is causing a force. (12.1) K/U
12. When two like magnetic poles are brought close to one another, they repel each other. (12.1) K/U
13. The magnetic field lines around a magnet often cross one another. (12.1) K/U
14. A compass always points to the magnetic north pole, even if it is near a stronger magnet. (12.2) K/U
15. Reversing the current in a wire also reverses the direction of the magnetic field. (12.2) K/U
16. Michael Faraday created the first electric motor based on Oersted's work on magnetism and electricity. (12.5) K/U
17. Adding a soft-iron core is the only way to increase the strength of a DC motor. (12.6) K/U
18. One way a simple DC motor can be improved is to increase the number of splits in the split ring commutator. (12.6) K/U

To do an online self-quiz,
GO TO NELSON SCIENCE

CHAPTER 12 REVIEW

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

Knowledge

For each question, select the best answer from the four alternatives.

1. Which of these best describes the location of Earth's magnetic field? (12.1) K/U
    - (a) only inside Earth
    - (b) surrounding Earth
    - (c) outside Earth's atmosphere
    - (d) both inside and surrounding Earth
2. The first compasses were most likely made of which material? (12.1) K/U
    - (a) soft iron
    - (b) magnesium
    - (c) copper
    - (d) magnetite
3. Magnetic field lines
    - (a) sometimes cross each other
    - (b) point from south to north outside a magnet
    - (c) are farther apart where the magnet is stronger
    - (d) point from south to north inside a magnet (12.1) K/U
4. Which best describes the force created when the north poles of two magnets are brought together? (12.1) K/U
    - (a) resonant
    - (b) negligible
    - (c) repulsive
    - (d) attractive
5. When using the electron flow model to illustrate electrical current in a straight wire, what rule is used to determine the direction of the resulting magnetic field? (12.2) K/U
    - (a) right-hand rule for a straight conductor
    - (b) left-hand rule for a straight conductor
    - (c) conventional current method
    - (d) right-hand rule for solenoids
6. A version of the right-hand rule can be used to determine which of the following? (12.2, 12.4, 12.5) K/U
    - (a) direction of the magnetic field created by a current-carrying straight wire
    - (b) direction of the magnetic field created by a current-carrying solenoid
    - (c) direction of the force on the current-carrying conductor of an electric motor
    - (d) all of the above

Match each name on the left with the most appropriate contribution on the right.

7.

(a)	Magnes of Magnesia	(i)	showed that a magnetic field surrounds a current-carrying wire
(b)	Hans Christian Oersted	(ii)	created the first electric motor
(c)	André-Marie Ampère	(iii)	ancient Greek shepherd who discovered magnetite
(d)	Michael Faraday	(iv)	found that two wires with opposite currents created a repulsive force (12.1, 12.2, 12.4, 12.5) K/U

Write a short answer to each question.

8. What fields are present around a massive magnet, such as Earth? What technology could be used to detect the presence and direction of at least one of the fields? (12.1) K/U
9. A current is directed into a straight conductor oriented perpendicular to the page. The current goes into the page. What shape and in which direction are the magnetic field lines? (12.2) K/U
10. Explain how the use of fields can be applied to transmitting electrical energy without wires. (12.3) K/U
11. The attraction of two wires with current going in the same direction tells us what about their magnetic fields? (12.4) K/U
12. Solenoids are often used as controllable bar magnets. Describe how the magnetic field lines of a bar magnet and the magnetic field lines of a solenoid are similar to each other. (12.4) K/U C
13. State the right-hand rule for a solenoid. (12.4) K/U
14. In Michael Faraday's first electric motor, what interacted with the magnetic field of the bar magnet to cause the motion of the motor? (12.5) K/U
15. (a) According to the motor principle, what happens to a current-carrying conductor as it cuts across external magnetic field lines?
    (b) What factors determine the magnitude of this effect on the current-carrying conductor? (12.5) K/U
16. One of the first practical uses of the motor principle was the development of analog meters. What is the main advantage of an analog meter compared to a modern digital meter? (12.5) K/U

17. (a) What did the invention of the split ring commutator allow a DC motor to do?
    (b) What other developments have improved the design of DC motors? (12.6) K/U

Understanding

18. Earth has both a magnetic field and a gravitational field. (12.1) K/U
    (a) What is the difference between these two fields with respect to the direction of the forces they cause?
    (b) What is the difference between these two fields with respect to the materials that they act upon?

19. (a) Draw the magnetic field lines created by two bar magnets held close together with one north and one south pole facing each other.
    (b) Draw the magnetic field lines created by two bar magnets held close together with their north poles facing each other.
    (c) How would your illustration from (b) change if the magnets were held with their south poles facing each other? (12.1) K/U C

20. In the images in **Figure 1**, there is a mistake in the field lines. Copy each image and correct the mistake. (12.1) T/I

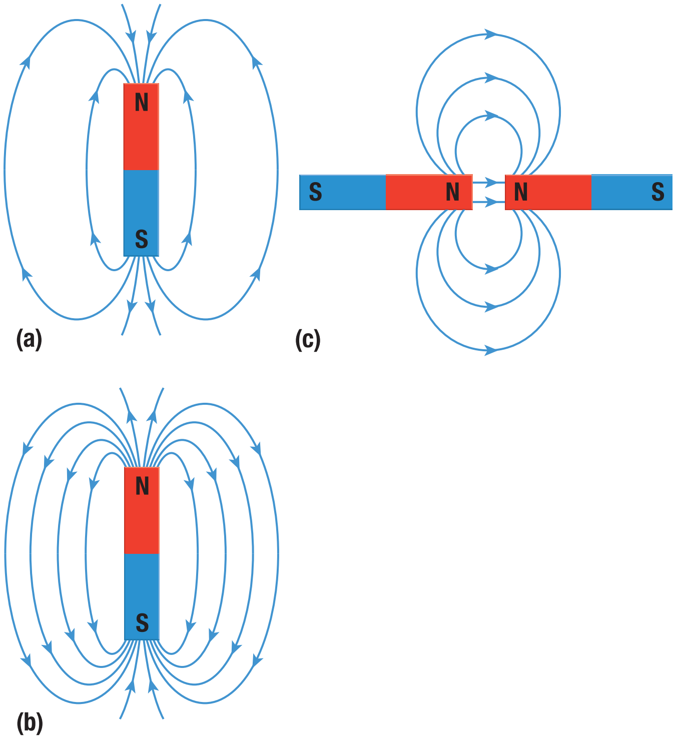


Figure 1

21. Describe why iron filings are useful for understanding magnetic fields. (12.1) K/U C

22. Describe how various magnets are used in the Maglev train in Shanghai and in what direction the magnetic forces are acting. (12.1) C A

23. Many physicists had hypothesized that electric currents produce magnetic fields, but Hans Christian Oersted was able to confirm the hypothesis. (12.2) K/U
    (a) How did Oersted confirm that electric currents produce magnetic fields?
    (b) What further details did Oersted's method of testing his hypothesis provide about these magnetic fields?

24. What is the main similarity between the behaviour of charged particles and that of magnetic poles? (12.2) K/U

25. (a) How do the models of conventional current and electron flow differ from each other?
    (b) How do conventional current and electron flow affect how we determine the direction of a magnetic field around a straight wire? (12.2) K/U

26. Using the page as a frame of reference and applying the right-hand rule, determine the following: (12.2) T/I
    (a) What is the direction of the current that produces a counterclockwise magnetic field on the page?
    (b) What is the direction of the magnetic field produced by a current flowing into the page?

27. Determine the direction (clockwise or counterclockwise) of the magnetic fields produced by the currents in **Figure 2**. (12.2) T/I

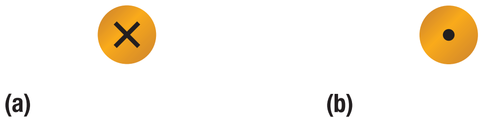


Figure 2

28. Which direction on the compass will the needle point for each scenario in **Figure 3**? (12.2) T/I

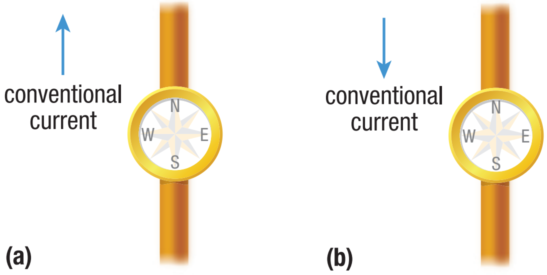


Figure 3

29. Determine the direction of the current for the magnetic field shown in **Figure 4**. (12.2) T/I

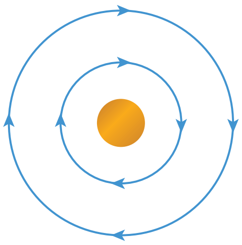


Figure 4

30. What conclusion did Ampère draw from his experiments with two current-carrying wires? (12.4) K/U

31. Two parallel wires are each carrying a current. There is a magnetic force of attraction between the two wires. (12.4) T/I C
    (a) What do we know about the directions of the currents, based on the magnetic force?
    (b) What kind of magnetic force would be produced if both of the currents in the wires were reversed?
    (c) What kind of magnetic force would be produced if only one current was changed?
    (d) What would the effect on the magnetic force be if the currents were increased?
    (e) What would the effect on the magnetic force be if one current was increased and the other current was switched off?

32. (a) Use your own words to describe a solenoid.
    (b) Draw a current-carrying solenoid. Label the direction of the current, the magnetic field lines, and the north and south poles of the solenoid. (12.4) K/U C

33. There is a mistake in **Figure 5**. Copy the image and correct the mistake. (12.4) T/I A

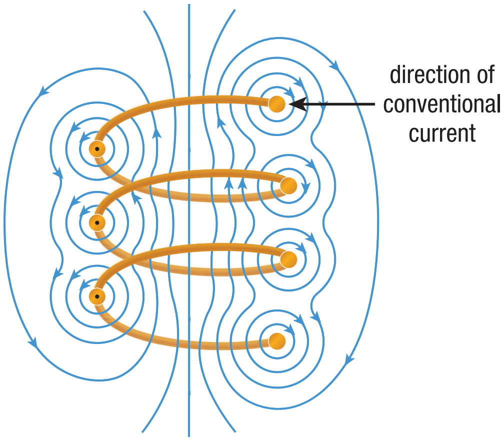


Figure 5

34. Explain how the right-hand rule for a solenoid helps us to understand the operation of a solenoid. (12.4) K/U

35. (a) Describe the effect of running a current through a wire suspended between the north pole of one magnet and the south pole of another magnet.
    (b) What is the effect of reversing this current?
    (c) Draw a diagram of the magnetic field lines of both of these cases and the direction of the resultant effects. (12.5) T/I C

36. Describe what is shown in **Figure 6** and explain how this simple diagram defines the fundamentals of the motor principle. Be sure to discuss the interaction between the magnetic field lines shown. (12.5) C A

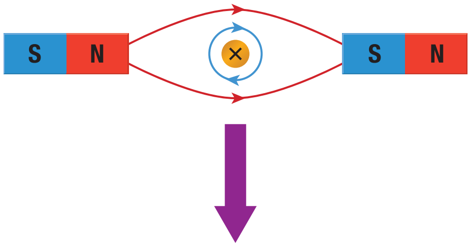


Figure 6

37. (a) Explain the right-hand rule for the motor principle.
    (b) Explain how you would orient your right hand to determine the direction of the force produced if the current moves toward the right and the external magnetic field is pointing upward.
    (c) Does the description in (b) result in a force into the page or out of the page? (12.5) T/I A

38. Galvanometers are used in circuits to measure electrical signals. (12.5) K/U C A
    (a) What two specific measurement devices contain a galvanometer? What electrical property does each measure?
    (b) Explain for each measurement device how the galvanometer is included in the circuit.

39. (a) Using your own words, explain the difference between a galvanometer and a DC motor.
    (b) What technology was used to make the transition between a galvanometer and a DC motor, and how does it work?
    (c) Draw and label a diagram of a simple DC motor. Be sure to include both moving and stationary components. (12.5, 12.6) C A

40. (a) List the major components of a DC motor. State whether each component is a stationary or a rotating part.
    (b) What is the name for the stationary parts of a DC motor? What is the name for the rotating parts of a DC motor? (12.6) T/I

41. (a) List three ways that the design of a DC motor can be improved.
    (b) If one of these three improvements is taken to an extreme, it becomes undesirable. Which is it and what is the risk that makes it less desirable than the other two? (12.6) K/U

42. Using your own words, describe the problem of a split ring commutator with a single split and describe the solution that DC motor designers came up with to overcome it. (12.6) K/U C

43. Explain the development of DC motors, beginning with Oersted's experiment and concluding with modern DC motors. (12.2, 12.5, 12.6) K/U C A

44. Discuss the strengths and weaknesses of each of the following medical imaging technologies: X-rays, ultrasound, and magnetic resonance imaging. (12.7) K/U A

Analysis and Application

45. Using your own words, describe how the aurora borealis is an effect of Earth's magnetic field that is observed as a display of light. (12.1) K/U C A

46. If a compass is moved away from a current-carrying conductor, eventually the needle of the compass will return to pointing toward Earth's magnetic north pole. (12.2) K/U C
    (a) What property of magnetic field lines does this illustrate?
    (b) How does the needle's return to Earth's magnetic north pole illustrate this property of field lines?

47. Describe three ways an electromagnet can be more advantageous than a permanent magnet, and provide a useful example for each. (12.4) C A

48. (a) Name a household object that uses a magnet.
    (b) Does this object use its magnet to interact with another magnet or does it use its magnetic field to produce a force on a metallic object?
    (c) Is the magnet used in this object a permanent magnet or an electromagnet?
    (d) Draw a diagram of how this object's magnet is used. Be sure to include field lines. (12.4) K/U T/I C

49. (a) A subwoofer uses a solenoid (voice coil) and a permanent magnet to create vibrations of the speaker cone. Describe the interaction between the solenoid (voice coil) and the permanent magnet.
    (b) If the quality of the speaker is in part defined by the strength of the solenoid, what properties should the solenoid of a high-quality speaker have? (12.4) K/U T/I C A

50. Study **Figure 7** carefully. Determine the magnetic poles on each of the coils at the bottom of the cores. What is the shape of the magnetic field similar to? (12.4) T/I A

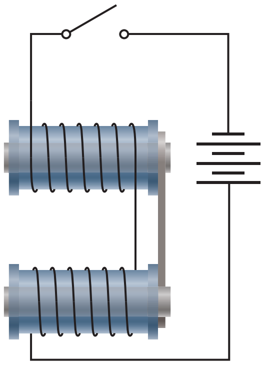


Figure 7

51. An MRI can use a magnetic field that is produced by one of three types of technology: an electromagnet, a permanent magnet or a superconducting magnet. An electromagnet would need many windings and a large electric current to produce a strong enough magnetic field for an MRI machine. Why would the electromagnet not be a desirable choice? (12.4) T/I A

52. Michael Faraday's experiment that resulted in the first electric motor was based on the idea of movement between a magnetic object and an external magnetic field. What is the fundamental difference between his motor and a compass, which is also a magnetic object moving due to an external magnetic field? (12.5) C A

53. In which direction will the galvanometer needle move in **Figure 8?** (12.5) T/I A

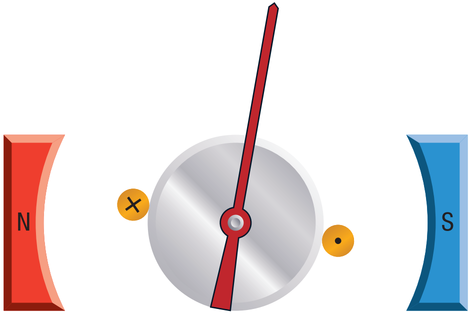


Figure 8

54. **Figure 9** shows a single-loop DC motor. Determine the direction of rotation of the loop. (12.6) T/I A

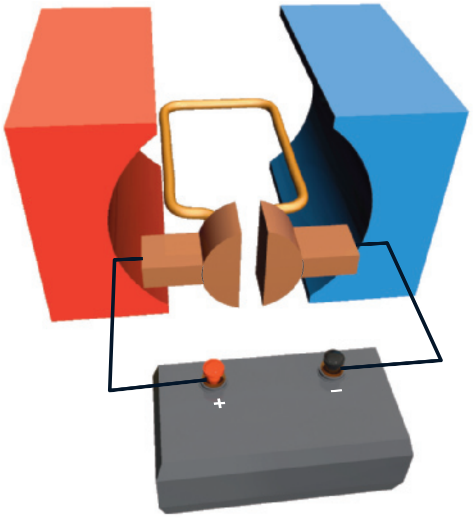


Figure 9

55. What should the external magnet poles be in order for the motor in **Figure 10** to spin counterclockwise? (12.6) T/I A

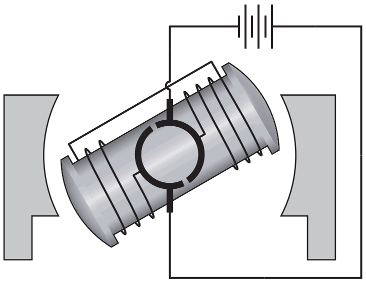


Figure 10

56. A DC motor can be made to spin faster or slower by altering the current. A variable resistor is a device that can vary its electrical resistance by typically rotating a dial. How could a motor and a variable resistor be used in a variable speed electric drill? Explain your answer. (12.6) T/I A

57. Copy and complete **Table 1** by filling in what change to the variable will cause either an increase or decrease in the strength/speed of the motor. (12.6) K/U T/I

Table 1

Variable	Increase the motor strength/ speed	Decrease the motor strength/ speed
current		
number of loops		
type of armature		
strength of external magnets		

58. Suppose that instead of using permanent magnets for the external magnets in a DC motor you used electromagnets. Further suppose that the electromagnets are connected to the same external circuit as the brushes of the motor. Would it be possible to reverse the direction of rotation of this motor design? Explain. (12.4, 12.6) T/I A

59. (a) Describe how a gasoline-electric hybrid car uses an electric motor.
    (b) Describe the primary benefit of using electric motors in automobiles.
    (c) What factors prevent a hybrid car from being completely pollution free? (12.6) K/U A

Evaluation

60. Maglev trains use magnets to reduce friction and to produce forward motion. This is a replacement for wheels and steam engines. (12.1) K/U A
    (a) Describe a possible use of magnets to replace a component of the automobile. For example, describe how traditional brakes might be replaced by magnetic brakes.
    (b) Describe one benefit and one drawback of this use of magnets over conventional parts.
    (c) Describe how some other familiar technology could benefit from the use of magnets.

61. This chapter discusses both natural magnetic phenomena and technologies where magnetism can be manipulated by humans. Compare natural magnetic occurrences with any of the human-made technologies discussed. List the differences and the similarities. (12.1, 12.4, 12.6, 12.7) K/U C A

62. Compare two innovations that use electromagnetism. Describe the ways electromagnetism is used to produce the desired effect and the impact of the technologies on daily life and society at large. (12.4, 12.6, 12.7) K/U A

Reflect on Your Learning

63. Describe several ways in which Oersted's experiments with electric current have shaped technology today. C A

64. To understand the impact of electromagnetism on our everyday lives, keep a journal of all your interactions with DC motors for an entire day. Remember that computer fans and hard drives, DVD players, electric car windows, and vacuum cleaners, among many other objects, all use DC motors to make objects rotate. Make your list as complete as possible. K/U C A

65. Pick an everyday item that uses electromagnetism. Describe how your daily life would change without that item. For example, without speakers, we would have no cellphones. C A

Research

GO TO NELSON SCIENCE

66. The Large Hadron Collider (LHC) is one of the largest scientific undertakings in human history. It relies heavily on electromagnets to control the path and the speed of particles within the accelerator. Choose one of the following topics and write a short report about your findings:
    - the use of electromagnets within the LHC
    - the research goals of the particle accelerator
    - the recent results of testing at the LHC T/I C A

67. The aurora borealis and aurora australis (the northern and southern lights) have been topics of discussion in both mythology and science. Research an ancient mythological explanation for the northern lights. Write a paragraph comparing the mythological explanation with the current scientific understanding of the aurora. T/I C A

68. Nikola Tesla dreamed of transmitting electrical energy without using electricity grids. Research some of the potential applications of wireless electricity today and the consequences that these applications could have on everyday life. Create a slide presentation that summarizes your findings. T/I C A

69. Many companies are developing and producing electric vehicles. Research one company. T/I C A
    (a) Write a brief history of the company.
    (b) Does the company boast any specific technological advances over its competitors? If yes, what is it? If no, how does the company plan to gain a competitive edge?
    (c) Write a paragraph or two describing any of the company's major successes or failures.
    (d) What is your impression of the vehicles produced by this company? Be sure to back up your arguments with reasoning.

70. Solenoids are used in subwoofers, electric bells, and cars, among other applications. Research other uses for solenoids. Write a short report that includes a discussion of the application and a diagram of how the solenoid is employed. T/I C A

71. A mass spectrometer (**Figure 11**) measures the mass and relative concentrations of atoms and molecules using magnetic fields. For example, a scientist can take a sample of pure carbon and, by using a mass spectrometer, find that it contains two different forms of carbon (isotopes): carbon-12 and carbon-13. The mass spectrometer can also be used to identify the quantity of compounds in a mixture. Research how a mass spectrometer uses magnetic fields to separate compounds or elements in a mixture. Also include in your research some of the incredible detection capabilities of a mass spectrometer when attached to a gas chromatograph. Write a short report of your findings. T/I C A

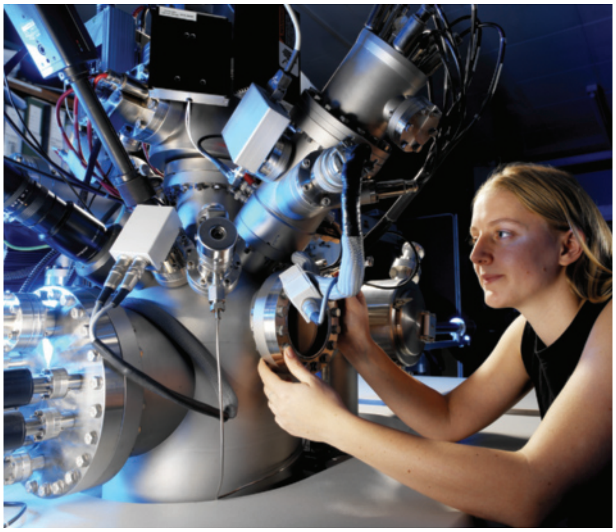


Figure 11

CHAPTER 13 Electromagnetic Induction

KEY CONCEPTS

After completing this chapter you will be able to

- describe the law of electromagnetic induction
- use Lenz's law to predict the direction of induced current
- describe alternating current and its properties
- describe the operation of an alternating current generator
- describe how transformers rely on alternating current to step up or step down the voltage
- describe how generators, transformers, and the electrical grid work to provide electricity

Can Magnetic Fields Create Electric Currents?

The Back Lot Stunt Coaster at Canada's Wonderland is a different type of roller coaster. On most roller coasters, you are first slowly towed up a big hill and then released down the other side. This initial buildup of gravitational potential energy on typical roller coasters is necessary so that it can be converted into kinetic energy for the rest of the ride. In the Back Lot Stunt Coaster, you start horizontally and then accelerate rapidly from rest to 64 km/h in 3 s, which is a faster acceleration than many sports cars. How is it done? The ride is accelerated using a linear induction motor.

In Chapter 12, you learned about direct current motors and how they convert electrical energy into rotation. Linear induction motors use electrical energy to create a magnetic field that can cause an object to move along a linear track instead of rotating on the spot. These motors cause huge accelerations. The linear induction motor is being tested for installation in the next generation of aircraft carriers to replace the steam catapult system currently being used. As an example, an aircraft must reach a takeoff speed of 241 km/s in just 3.0 s. For comparison, a high-end sports car can only reach 100 km/h in 3.5 s.

The linear induction motor could also be used to put spacecraft into space. Chemical rockets are currently used, but they are expensive, and there are negative environmental effects from the exhaust gases and waste produced when a chemical rocket is fired. One idea being considered is to use a linear induction motor to accelerate a spacecraft up to one and a half times the speed of sound and then let jets or rockets accelerate the craft to higher velocities and into space. The major benefits of using this approach are reliability, weight reduction, and less pollution.

In this chapter, you will learn about electromagnetic induction and its many applications, from amusement park rides to one of the most important applications of all: generating electrical energy.

STARTING **POINTS**

Answer the following questions using your current knowledge. You will have a chance to revisit these questions later, applying concepts and skills from the chapter.

1. How can a magnetic field be used to induce an electric current?
2. Can you predict the direction of an induced electric current?
3. What properties of an alternating current make it favourable for electricity generation?
4. What is the most efficient way to transmit electrical energy?

Mini Investigation

Electric Current from Motion?

Skills: Performing, Observing

In this activity, you will try to produce an electric current in a loop of wire without touching it.

Equipment and Materials: galvanometer; loop of wire; bar magnet; alligator clip leads (if necessary)

1. Connect the loop of wire directly to the galvanometer.
2. Move the bar magnet in various directions around or through the loop of wire without touching the wire.
3. Observe any changes on the galvanometer, and record your results.

A. What types of motion cause a current in the wire? Explain. T/I

B. Is any one type of motion more effective at producing a current than the others? Explain. T/I

13.1 Electromagnetic Induction

You know from Chapter 12 that an electric current in a conductor can produce a magnetic field. Is the opposite also true? Can a magnetic field produce an electric current in a conductor? In 1831, Michael Faraday, an English scientist, proved that it could. This discovery led to many of the technologies that provide the electricity we use every day.

Discovery of Electromagnetic Induction

electromagnetic induction the production of electric current in a conductor moving through a magnetic field

law of electromagnetic induction a change in the magnetic field in the region of a conductor induces a voltage in the conductor, causing an induced electric current in the conductor

In Section 12.2 you learned that a constant electric current will produce a magnetic field, so it is logical to assume the opposite—that a constant magnetic field will produce an electric current in a conductor sitting in that constant magnetic field. It does not. Faraday discovered that in order to produce an electric current, the magnetic field needs to be continuously changing. He discovered **electromagnetic induction**, the production of electric current in a conductor within a changing magnetic field.

Induction means that one action causes another action to happen, often without direct contact. In his investigations, Faraday brought a permanent magnet near a conductor, but not in direct contact with it, and induced a current in the conductor. The electric current was produced only while the magnet was moving in the vicinity of the conductor. We call this an "induced current" because it is not an already existing current; it is formed by the action of the magnetic field moving along the conductor. These observations led Faraday to develop what is now known as the **law of electromagnetic induction**.

Law of Electromagnetic Induction

Any change in the magnetic field near a conductor induces a voltage in the conductor, causing an induced electric current in the conductor.

Mini **Investigation**

Faraday's Ring

Skills: Performing, Observing

SKILLS HANDBOOK A2.1

Electromagnetic induction can be investigated using a device containing two completely independent circuits. The primary circuit is connected to a source of electrical energy. The secondary circuit is connected only to a galvanometer.

Equipment and Materials: galvanometer; battery (or power supply); switch; alligator clip leads; 2 pieces of conducting wire; soft-iron ring

1. Construct a Faraday's ring apparatus as shown in **Figure 1**. Coil the conducting wire tightly around the ring. Be sure to coil the conducting wire the same number of times on each side of the ring.

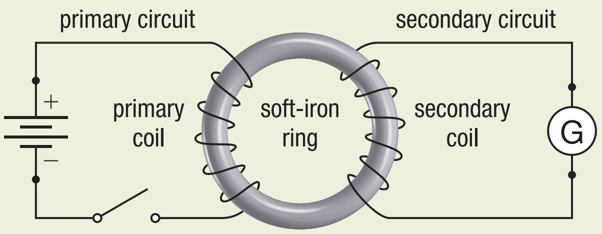


Figure 1 Faraday's ring

2. Close the switch in the primary circuit and observe the galvanometer in the secondary circuit.
3. Open the switch in the primary circuit and observe the galvanometer in the secondary circuit.

A. What happened to the galvanometer when the primary circuit switch was closed? T/I

B. What happened to the galvanometer when the primary circuit switch was open? T/I

C. Was there a difference in the direction of the current in Steps 2 and 3? T/I

The implications of this discovery were extraordinary because for the first time electricity had been generated using only a magnet. Before Faraday's experiments, the only way to produce electrical energy was to use an electric cell or battery. Batteries are extremely useful, but they have disadvantages. Batteries operate for a limited amount of time, can be heavy and bulky, and produce only small electric potential differences. With Faraday's discovery, all that was needed was to find a way to move the magnet continuously, and the world would be able to produce electrical energy on a large scale without the limitations of batteries.

Electromagnetic Induction and Faraday's Ring

Faraday (**Figure 2**) investigated electromagnetic induction using a device that he built himself, the Faraday's ring, which you constructed in the Mini Investigation. Closing the switch in the primary circuit produces a constant electric current in the conducting wire. This constant electric current produces a magnetic field in the primary coil. The soft-iron ring enhances the strength of the magnetic field, and the ring itself becomes magnetized. This change of the magnetic field in the soft-iron ring (from zero to some value) induces a voltage and an electric current in the secondary circuit. However, once the magnetic field is stable and no longer changing, the electric current in the secondary circuit no longer exists. Remember that you need a changing magnetic field to induce an electric current.

When the switch is opened, the magnetic field in the primary coil disappears, because there is no longer an electric current. The magnetic field in the soft-iron ring collapses from maximum strength to zero. This change in the magnetic field causes an induced electric current in the opposite direction in the secondary circuit. Direct currents only produce electromagnetic induction for brief instants when the primary circuit is switched on or off.

Figure 2 Michael Faraday was born on September 22, 1791, in London, England. At 14, he apprenticed with a local bookbinder. He read many of the books that were being bound and developed an interest in electricity and chemistry. He was never formally trained as a scientist, yet he still published several papers in scientific journals.

Factors Affecting Electromagnetic Induction

Several factors determine the amount of electric current that can be produced by electromagnetic induction. Each of the following factors must be considered independently.

Coiled Conductor

In Section 12.4, you learned that by coiling a conductor you can create a magnetic field similar to that of a bar magnet. The magnetic fields from both sides of the loop interact to produce a more pronounced magnetic field in the centre of the loop. Similarly, with electromagnetic induction, a coiled conductor has more induced electric current in it than does a straight conductor.

The Number of Loops in the Coil

You know from Section 12.4 that increasing the number of loops in a coiled conductor, or solenoid, produces a stronger magnetic field for a given electric current. With electromagnetic induction, the number of loops in the coil is directly proportional to the magnitude of the electric current induced in the conductor for a given change in the magnetic field. So, the greater the number of loops in a coil, the more electric current can be induced for a given change in the magnetic field.

The Rate of Change of the Magnetic Field

There are two cases to consider here: a coiled conductor with a permanent magnet and a Faraday's ring apparatus. In the case of a coiled conductor with a permanent magnet, the more quickly you move the magnet into, or out of, the coil, the greater is the rate of change you cause in the magnetic field within the coil. A higher rate of change causes a larger induced electric current in the conductor.

In the second case of Faraday's ring, the more quickly you increase the current in the primary circuit, the greater is the rate of change you cause in the magnetic field in the coiled conductor and the soft-iron ring. The magnitude of the induced electric current in the secondary circuit is proportional to the rate of change of the magnetic field in the soft-iron ring.

The Strength of the Inducing Magnetic Field

The stronger the inducing magnetic field, the greater is the induced electric current. So, a stronger permanent magnet induces a greater electric current in a given coil. Similarly, in a Faraday's ring, a greater electric current in the primary circuit increases the strength of the magnetic field in the coiled conductor and soft-iron ring. This increases the induced electric current in the secondary circuit.

Applications of Electromagnetic Induction

To operate any electrical device, you rely on electrical power produced and supplied through generators and transformers—both of which rely on electromagnetic induction to operate. You will learn more about generators and transformers in Sections 13.4 and 13.5. Now we will look at three other applications of electromagnetic induction: induction cooking, metal detectors, and induction chargers.

Induction Cooking

Cooking food involves the transfer of thermal energy. In an electric stove, an electric current is directed into the element, which converts the electrical energy into thermal energy. That thermal energy is transferred by conduction into a metal pot. The pot needs to increase in temperature to then transfer thermal energy into food. The efficiency of this process is low because the stove element has to get hot, the pot has to get hot, and finally the food is heated. In the process, much thermal energy is lost to the environment.

Cooking using an induction cooker involves a rapidly changing magnetic field in the stove element (**Figure 3**), which induces an electric current in the pot. The electric current heats the pot because of the electrical resistance of the pot. Iron pots work better than copper or aluminum due to their higher electrical resistance. Insulating materials like glass will not work on an induction cooker. Cooking with an induction cooker is more efficient because it is a more direct transfer of thermal energy to the food. Another benefit is that the induction cooking surface does not get hot, so food that spills onto the cooking surface does not burn. Since the induction cooking surface is not hot, the food immediately stops heating up once the induction cooker is turned off.

Figure 3 An induction cooking surface

Metal Detectors

Electromagnetic induction is also used to detect metals. Metal detectors use a coil that generates a rapidly changing magnetic field. This magnetic field induces a current in any metal near it. The induced electric current in the detected metal also produces an induced magnetic field of its own. Sensitive measurements of the magnetic field near a metal detector are used to detect the induced magnetic field.

Metal detectors have many uses and have become quite common. They are used for humanitarian purposes to help locate buried bombs called land mines. Land mines buried during times of war are often not removed and innocent people are injured or killed when walking through areas where no land mine warnings exist. Metal detectors are also used for security purposes at airports. If you have been on a commercial flight, you have walked through one of these detectors. Security guards use handheld devices to detect any metal objects (**Figure 4**). In addition, metal detectors are used by hobbyists searching for potentially valuable metals that might be buried in the ground.

Figure 4 Metal detectors like this one use electromagnetic induction.

Induction Chargers

Electromagnetic induction can be used to charge low-power electronic devices such as electric toothbrushes, or even cellphones. The charger is plugged into a wall outlet. Both the charger and the device to be charged contain a wire coil. When the device is placed on the charger an electric current is induced in the coil inside the device. This induced current charges the internal battery of the device. The benefit of this type of charging is that you do not need wires to plug directly into the device you wish to charge. Also, in the case of an electric toothbrush, the lack of direct electrical contact allows you to safely charge the device even if it is wet. If you have several devices that need charging, you can use a single charging station and simply place the devices you wish to charge onto the station. The disadvantage of induction charging is that you require a special attachment to connect to the device you wish to charge. Also, charging by induction is less efficient because energy can be transformed into an unusable form during the transfer.

13.1 Summary

- The law of electromagnetic induction states that a change in the magnetic field in the region of a conductor induces a voltage in the conductor, causing an induced electric current in the conductor.
- Faraday's ring is a device that demonstrates electromagnetic induction. A current in the primary coil creates a magnetic field in the ring. The magnetic field in the ring then induces a current in the secondary coil.
- The amount of induced electric current can be increased by coiling the conductor, increasing the number of loops, increasing the rate of change of the magnetic field, or increasing the strength of the magnetic field.
- Electromagnetic induction is used in many technologies, including generators, transformers, induction cooking, metal detectors, and induction chargers.

13.1 Questions

1. A student demonstrates electromagnetic induction using a straight wire and a permanent magnet. The wire is part of a circuit that is connected to a galvanometer. What would you expect to happen in each of the following scenarios? K/U
   (a) The magnet is placed on top of a stationary wire.
   (b) The magnet is removed from the top of the stationary wire.
   (c) The magnet is moved slowly over the top of the stationary wire.
   (d) The magnet is moved quickly over the top of the stationary wire.
   (e) The magnet is moved quickly back and forth over the stationary wire.
   (f) The wire is moved quickly past the stationary magnet.
2. You need to demonstrate electromagnetic induction and wish to maximize the amount of induced current. Describe a design to accomplish this. T/I C
3. A glass cooking pot with an iron handle is placed on the cooking surface of an induction cooker. Describe the temperature of the glass and the handle after being on the induction cooker for some time. K/U
4. Could you design a non-metal detector that detects things other than metal and uses electromagnetic induction? Explain. K/U
5. Before going through a metal detector at an airport, you may have to remove your belt, empty your pockets, and remove your shoes. Explain why. C A
6. List some devices for which induction chargers could be used. Do you think the benefits outweigh the disadvantages? Explain your answer. T/I A

13.2 Lenz’s Law

In 1834, Heinrich Lenz, a Russian physicist, formulated a law to describe the direction of induced electric current. He used logic and the law of conservation of energy to deduce the direction of an induced current. You can observe the direction of current by watching a needle on a galvanometer move as you move a magnet along a conductor. Lenz determined how to predict that direction.

Mini **Investigation**

Observing the Direction of an Induced Current

Skills: Predicting, Performing, Observing, Analyzing

SKILLS HANDBOOK **A2.1, A2.4**

In this activity, you will observe the direction of the induced current when moving a magnet into and out of a coiled conductor.

Equipment and Materials: galvanometer; coiled conductor; permanent bar magnet; 2 alligator clip leads

1. Connect the two terminals of the coil to the galvanometer.
2. At a moderate rate, push the north pole of the magnet into the coil (**Figure 1**). Note the direction of the current on the galvanometer.

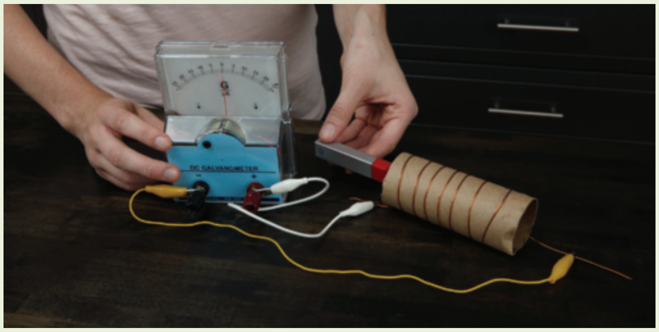


Figure 1

3. Pull the north pole of the magnet out of the coil and note the direction of the current on the galvanometer.
4. Repeat Steps 2 and 3 with the south pole of the magnet.

A. How did the direction of the current compare in Steps 2 and 3? T/I

B. Describe the direction of the current in Step 4 compared to Steps 2 and 3. T/I

C. Did using the south pole instead of the north pole change your results? Explain. T/I

D. Predict the magnetic pole induced at the end of the coil nearest the magnet (using the right-hand rule for a coiled conductor) for both Steps 2 and 3. T/I

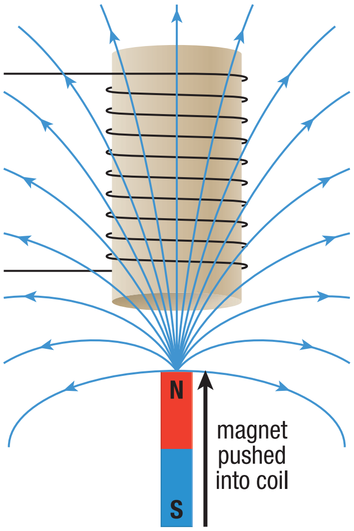


Figure 2 North pole of a permanent magnet pushed into a coiled conductor

Direction of Induced Current

When a permanent magnet is pushed into a coiled conductor, the electrons in the coil respond to the magnetic field by starting to move in a particular direction and forming an electric current. The direction of the current depends on the direction in which the magnetic field points. For example, if the north pole of a magnet is pushed into a coil, an induced current is produced in the coil in one direction (**Figure 2**). If the south pole of the magnet is pushed into a coil, the induced current is in the opposite direction.

How did Lenz deduce the direction of an induced current? He used the law of conservation of energy as a starting point. Recall from Chapter 5 that energy cannot be created or destroyed. All that can be done is to transform one type of energy into another. When the north pole of a magnet is moved into the coil, as in Figure 2, kinetic energy exists in the movement of the magnet. The kinetic energy is transformed into electrical energy in the electric current in the coil. As a result, the electric current in the coil also produces a magnetic field. Which way does the magnetic field point? Is the end of the coil nearest the bar magnet in Figure 2 a north magnetic pole or a south magnetic pole?

Let us first consider that the conventional induced current goes around the coil from left to right at the front of the coil in Figure 2. In this case, the right-hand rule for a solenoid would indicate that the bottom of the coil is a south magnetic pole. However, this is inconsistent with the law of conservation of energy! If the bottom of the coil were a south magnetic pole, then it would attract the north pole of the magnet into the coil without the need for an external force to push the magnet into the coil. So the bottom of the coil cannot be a south magnetic pole.

Now consider that the conventional induced current goes around the coil from right to left at the front of the coil. The right-hand rule for a solenoid would indicate that the bottom of the coil is a north magnetic pole. The permanent magnet is then repelled by the north magnetic pole of the coil. Therefore, you need to apply a force to push the permanent magnet into the coil, thereby doing work. You are transforming kinetic energy into electrical energy in the coil. This idea is consistent with the law of conservation of energy.

With similar deductive reasoning, Lenz was able to summarize his findings into a law for determining the direction of an induced current, known as **Lenz's law** (**Figure 3**).

Lenz's law if a changing magnetic field induces a current in a coil, the electric current is in such a direction that its own magnetic field opposes the change that produced it

Lenz's Law

If a changing magnetic field induces a current in a coil, the electric current is in such a direction that its own magnetic field opposes the change that produced it.

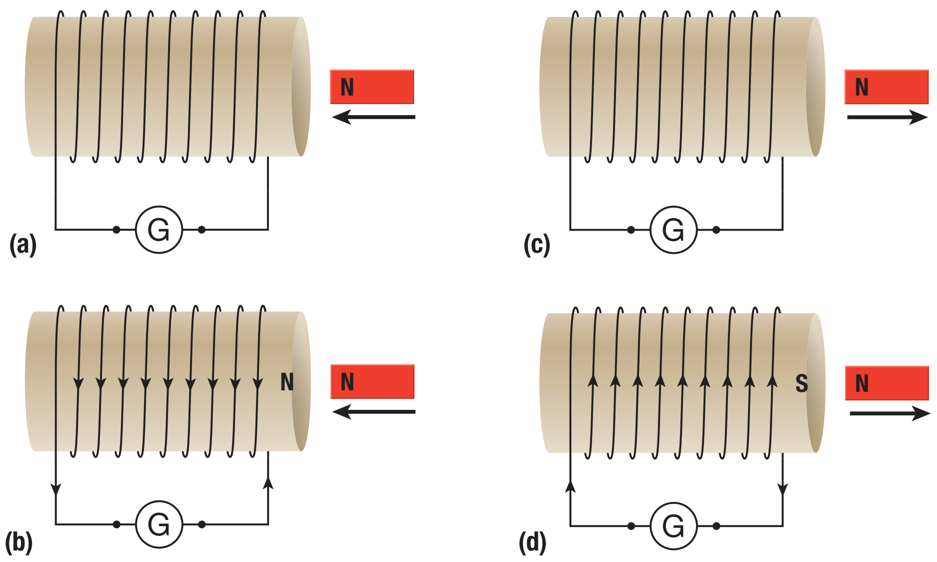


Figure 3 Lenz's law

(a) The permanent magnet is being forced into the coil. If north is being forced inward, the coil must oppose that with a north pole on the right side of the coil.
(b) If the right side of the coil must be north, then the right-hand rule for a solenoid determines the direction of the electric current to be down the coil at the front.
(c) The permanent magnet is being pulled out of the coil. If north is being forced to the right, the coil must oppose that with a south pole at the right side of the coil.
(d) If the right side of the coil must be south, then the right-hand rule for a solenoid determines the direction of the electric current to be up the coil in the front.

LEARNING **TIP**

Remembering Lenz's Law

The coil opposes whatever the magnet is trying to do. If north is moving in, the coil repels it with a north. If north is moving out, the coil attracts it back with a south.

Lenz’s Law and Drop-Tower Rides

Drop-tower rides are popular attractions at amusement parks (**Figure 4**). Riders are strapped into a seat and can be lifted to a height of over 70 m. They are then released to free fall toward the ground. To prevent disaster, the braking system must be extremely reliable. If a friction-based braking system were used, it would need to be triggered at just the right time, and the brakes would wear out quickly and need constant replacement. Drop-tower rides use an ingenious system that relies on electromagnetic induction. It can be explained using Lenz’s law.

Figure 4 Drop-tower rides use an electromagnetic braking system that is reliable and automatic and has parts that do not wear out.

Each cart on the ride has permanent magnets under the seats. After approximately 45 m of free fall, an electromagnetic braking system kicks in. Along the bottom third of the tower are copper strips mounted vertically on the tower. When the cart falls and the permanent magnets move past the copper conductor, an electric current is induced in the copper. The induced current then produces a magnetic field. Applying Lenz’s law, the induced magnetic field must oppose the field that created it. The opposing repulsion force acts to create a reliable, no-friction braking system.

Investigation 13.2.1

Investigating Electromagnetic Induction (p. 613)
Now that you have learned about electromagnetic induction, you can do some further observation by completing Investigation 13.2.1.

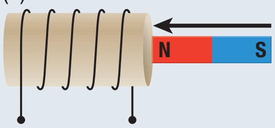
13.2 Summary

- Lenz’s law states that if a changing magnetic field induces a current in a coil, the electric current is in such a direction that its own magnetic field opposes the change that produced it.

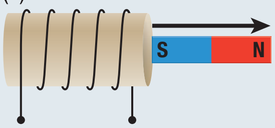
13.2 Questions

1. For each diagram below, determine the direction of the induced current in the coil and the magnetic poles on the coil. T/I

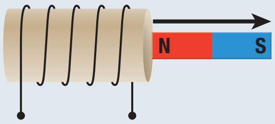
(a)



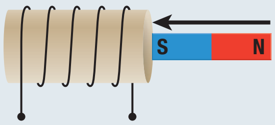
(c)



(b)



(d)



2. How would your answers to Question 1 change if the coils were moved and the magnets were stationary? Assume the coils were moved in the opposite direction to the arrows shown. K/U
3. When a magnet is pushed into a coil to induce a current, the magnetic field that is created never attracts the magnet into the coil. Explain why this is the case. K/U
4. In a drop-tower ride, would using an electromagnet in the carts, instead of the permanent magnets under the seats, work equally well? Would it be equally reliable? Explain. A

Alternating Current

13.3

You know that Faraday's law of electromagnetic induction requires a changing magnetic field to produce an electric current. If you push a permanent magnet into a coil, an electric current is produced while the magnet is moving. Lenz's law predicts the direction of the current. However, the current goes in one direction for only as long as you move the magnet in one direction. It is not possible for you to move the magnet into the coil in the same direction indefinitely. At some point, you will need to pull the magnet in the opposite direction. As soon as you reverse the direction of the magnet, the electric current also reverses direction. A current that periodically reverses direction is called an **alternating current**.

alternating current an electric current that periodically reverses direction

Development of Alternating Current

Recall from Section 11.5 that direct current is a flow of electrons in one direction only. To cause an electric current, a potential difference is applied across the circuit by a source of electrical energy, such as a battery. This causes the electrons present throughout the circuit to move in one direction. Charges flow from one terminal of the battery through the circuit and eventually back to the other terminal. This situation describes the current in the small circuits you studied in Chapter 11. Do the principles involved in these small circuits apply to a large circuit like the circuits in your home or even the electrical power grid?

Today's electrical power grid does not rely on direct current. The transfer of electrical energy using direct current is limited to how far it can be transferred without significant energy loss in the form of thermal energy. However, direct current was the standard used in the first electrical power grids. In 1882, Thomas Edison built the Pearl Street power station in Manhattan to illuminate homes and stores. He set up an electrical power grid using direct current, but he was only effectively able to transfer electrical energy to 193 buildings.

Nikola Tesla, an inventor and electrical engineer, developed a competing system that used alternating current. The alternating current system could transfer energy from a power plant more efficiently than the direct current system could. In 1896, the Edward Dean Adams Station, a United States hydroelectric power station, delivered the first alternating current along a power grid to the city of Buffalo.

Edison and Tesla both fought to have their systems accepted, but in the end alternating current became the favoured choice. In 1922, the Sir Adam Beck Generating Station started producing alternating current electricity in Niagara Falls, Canada.

WEB **LINK**

To find out more about Tesla's and Edison's battle for electrical power distribution,

GO TO NELSON SCIENCE

What Is Alternating Current?

Alternating current is a back and forth motion of charges. To understand alternating current, look at the graphs of current and voltage versus time in **Figure 1**.

As the voltage, *V*, increases, the conventional current, *I*, in the wire increases in a positive direction. The voltage increases until it reaches a maximum positive value. At the same instant, the current also reaches a maximum positive value. The voltage then decreases through zero until it reaches a maximum negative value. The current similarly decreases.

In Figure 1, the process repeats at a frequency of 60 Hz, which is the frequency of electricity in the North American electrical power grid. This means that the current is going in a positive direction, reversing, and going in a negative direction 60 times each second. So the electrons in the wire never travel the complete length of the circuit; rather they move back and forth in about the same spot. Note that the graphs both go through zero twice during each cycle as the current is changing directions. This implies that the circuit is effectively off for an instant. You may ask why we do not notice this effect. In fact, lights do get dimmer and brighter during each cycle, but the cycles occur so quickly that our eyes cannot detect them.

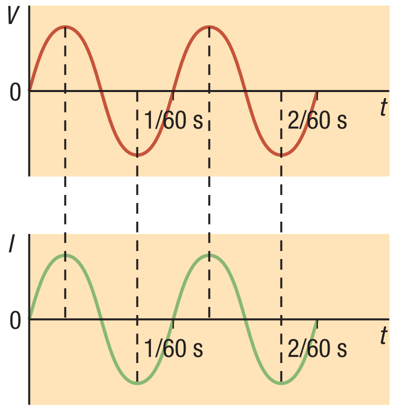


Figure 1 Voltage and current versus time for an alternating current. Note the frequency of 60 Hz.

Since the electrons move back and forth in about the same spot, you may think the current is ineffective at transferring energy. To understand how an alternating current can cause an energy transfer, consider a clothes washing machine. In a washing machine, an agitator swishes the wet clothes back and forth. The agitator still causes changes in energy, and thus work is done to clean the clothes. In an alternating current circuit, electrons move back and forth to cause energy changes in the electrical device, and thus work is done.

All the relationships that you have learned involving circuits and their components, for example, Ohm's law, still apply with alternating current. In the graphs in Figure 1 on the previous page, as the voltage increases, so does the electric current. This is in accordance with Ohm's law, and the current depends on the resistance of the wire that is used to carry the alternating current.

Household Circuits

There are limits to how much alternating current homes can draw. Smaller homes and apartments may only require 50 A to 100 A of electric current. Larger homes require 150 A to 200 A of electric current. The wire that enters your home from the electrical power grid is called the service line, and the amount of current it carries is labelled at the point of entry. For example, you may have a 100 A service going to your home. The service enters your distribution panel, which controls all the circuits in your home (**Figure 2**).

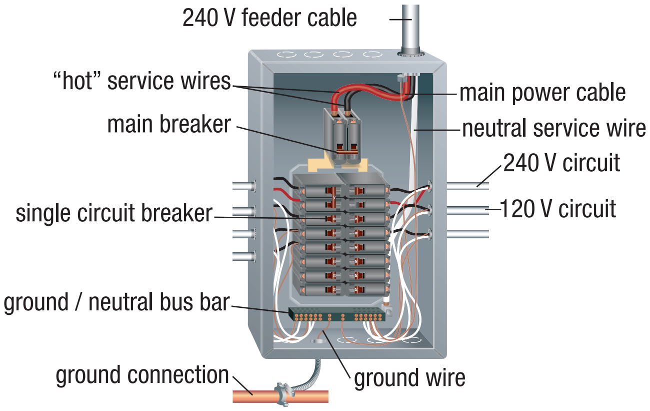


Figure 2 A distribution panel controls all of the circuits in your home. You can think of this panel as the power supply for your home. Note the red, black, and white service lines.

The AC voltage oscillates between a maximum positive voltage and a maximum negative voltage. Since the maximum voltage is reached for a brief instant twice during a cycle, we do not state that voltage. Instead, we use a value that is called the root mean squared or RMS value. This is an effective voltage that is available most of the time during a cycle. It also allows for the use of one voltage in calculations instead of a constantly changing voltage.

Your home is designed so that an effective voltage of 240 V is applied to the electrons in the wires in your home. Only a few of your household appliances require 240 V, such as an electric stove or clothes dryer. Most appliances require an effective voltage of only 120 V. To accommodate both requirements, a three-wire system is used. Two of the wires are considered "hot" and are coloured red and black. The third wire is white and is called the neutral wire. The voltage between the black and the white, and the red and the white, is 120 V. The voltage between the red and the black is 240 V. This way, an electrician can wire the home's circuit with just two of the wires. Typically, the electrician uses only the black and white wires when 120 V is required. If an appliance requires 240 V, then the black and red wires are used.

CAREER **LINK**

Electricians must have an understanding of the electrical requirements of appliances to wire homes. To find out more about becoming an electrician,

GO TO NELSON SCIENCE

A fourth wire, called the ground wire, is another essential part of the wiring. Ground wires can be bare (not insulated) or green and are electrically connected to the ground via your electrical distribution panel. The purpose of the ground wire is to prevent stray currents from reaching you when you touch a circuit and to direct them safely into the ground. As a safety feature, all electrical receptacles and switches must be grounded.

The receptacles for 240 V appliances and 120 V appliances are different. A 240 V plug may have four prongs, one for each of the wires: red, black, white, and bare (or green) (**Figure 3**). Most 120 V plugs require three prongs, one each for black, white, and ground. There are also many devices, such as lamps, that use two-prong plugs and do not have a ground pin.

Some electronic devices (such as laptop computers) require direct current because they cannot operate with alternating current. These electronic devices need an adapter that converts the alternating current into direct current. The electrical requirements of some common household appliances are listed in **Table 1**.

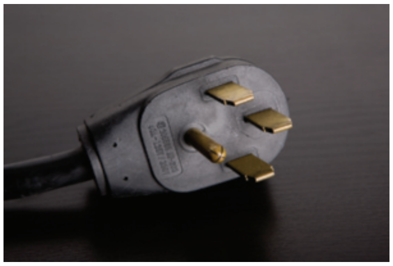


Figure 3 A plug for an electric stove or clothes dryer is designed for a maximum alternating current of 30 A at 240 V. Since it has four prongs, it can also supply 120 V for parts of the appliance that do not require 240 V (such as control circuits).

Table 1 Electrical Requirements of Some Common Household Appliances

Device	Type of current required	Current requirements (A)	Voltage requirements (V)
electric stove	AC	30	240
clothes dryer	AC	30	240
air conditioner	AC	20	240
iron	AC	5	120
hair dryer	AC	12.5	120
refrigerator	AC	6	120
40-inch LCD television	DC	18	12
desktop computer (excluding monitor)	DC	0.5 to 20 (depends on the component)	0.8 to 12 (depends on the component)
telephone charger	DC	1	5

Safety Systems

Many safety systems exist in your home to prevent harm to you, damage to your appliances, or electrical fires. These include fuses, circuit breakers, ground fault circuit interrupters, and arc fault circuit interrupters.

Fuses

Fuses are devices that are placed in series with one of the parallel branches in your home. If the current exceeds the maximum value at which the fuse is rated, the wire inside the fuse melts, which opens the circuit and prevents any more current. Fuses are for single use only. Fuses may also be found inside appliances as a further measure of protection.

Circuit Breakers

Circuit breakers are devices that prevent too much current in a wire for an extended period of time. If too much current is in a wire, the wire will heat up and the insulation may melt and potentially cause a fire. Circuit breakers work by using a strip of two different metals fused together. The strip of fused metals is called a bimetallic strip.

When too much current is present, the bimetallic strip heats up and bends. This causes the breaker to "trip," which turns off the circuit. If a circuit breaker trips, you should consider why it tripped. It could be because too many loads are connected in parallel to the same circuit and require too much current. Using fewer electrical devices on that circuit should prevent the tripping. Circuit breakers are reusable and can be reset.

Ground Fault Circuit Interrupters

Ground Fault Circuit Interrupters (GFCIs) are installed in places like bathrooms. Their purpose is to detect any differences in the current going into a circuit compared to the current going out. If the GFCI does detect a difference, it immediately shuts off and stops the current. Suppose that you touch an electrical outlet with a wet hand and then reach for an appliance with another wet hand. It is possible that you may set up a circuit pathway for electric current to travel through your body. This could cause electrocution. The GFCI very quickly detects the difference in current and immediately turns off the circuit. GFCIs respond much more quickly than regular circuit breakers because they are designed to trip with a small current fault, whereas regular circuit breakers will only trip if the current exceeds the maximum rating. For example, a GFCI will trip if a current difference of 0.006 A is detected, whereas a current of over 15 A needs to be detected to trip a regular breaker.

Arc Fault Circuit Interrupters

Arc Fault Circuit Interrupters (AFCIs) prevent sparking or arcing, which could start a fire. Arcing occurs when electric current travels through the air and causes a spark. This may happen if the insulation around the wiring has become frayed. The bare wire can possibly move close to a metal part and cause arcing to occur. The temperature of an arc is very high and could cause a fire. Arcing may not be enough to cause a circuit breaker to trip, so the AFCI prevents current flow if an arc is detected. AFCIs also act more quickly than regular circuit breakers.

13.3 Summary

- Alternating current is an electric current that periodically reverses direction.
- Alternating current frequency is 60 Hz in the North American electrical power grid.
- Some appliances require alternating current, whereas others require direct current.
- Your home requires a certain amount of current at voltages of 120 V and 240 V.
- The circuits in your home are protected by fuses, circuit breakers, ground fault circuit interrupters, and arc fault circuit interrupters.

13.3 Questions

1. Do electrons travel from the power plant to your home to provide electrical energy? Explain your answer. K/U
2. In alternating current electricity, is the voltage proportional to the current? Explain. K/U
3. (a) Would you notice if the frequency of the alternating current electricity were reduced to 2 Hz? Explain.
   (b) In the late 1950s, the frequency of alternating current was changed from 25 Hz to 60 Hz. Suggest a reason for this change. K/U C
4. How do 120 V plugs differ from 240 V plugs? K/U
5. A laptop computer requires 12 V direct current, and yet it is plugged into a home's wall outlet. What must be involved to satisfy the requirements of the laptop? K/U
6. Describe the differences between fuses, circuit breakers, GFCIs, and AFCIs. K/U
7. Most household circuits in North America use 120 V, while in Europe 240 V is most commonly used. Research to find out why this difference exists. Is one system better than the other? 🌐 T/I

🌐 GO TO NELSON SCIENCE

Electricity Generation

The large-scale production of electrical energy that we have today is possible because of electromagnetic induction. The electric generator, which provides electricity for most places in the world, relies on the law of electromagnetic induction to operate. An **electric generator** is a device that transforms other forms of energy into electrical energy. These other forms of energy can include thermal, gravitational, or kinetic energy. As you know from Chapter 5, the energy used to power generators can come from either renewable or non-renewable sources, each with its own benefits, disadvantages, and environmental impacts to be considered.

electric generator a device that transforms other forms of energy into electrical energy

In Section 13.3, you learned that alternating current was chosen for the transmission of electrical energy. So we will first look at the generation of alternating current.

The Alternating Current Generator

Electromagnetic induction requires a changing magnetic field to produce an electric current. In an AC generator there are two ways of changing the magnetic field. Either a permanent magnet can be spun inside a coil or a coiled conductor can be spun inside a magnetic field. We will examine a coiled conductor consisting of a single loop of wire rotating inside a magnetic field.

The AC generator shown in **Figure 1** shows a single loop of conducting wire set between the poles of two permanent magnets. There are two slip rings and two brushes. Each slip ring is connected to a different side of the loop. Slip ring 1 is connected to the left side of the loop, while slip ring 2 is connected to the right side of the loop. The slip rings rotate with the loop. The brushes are stationary and make contact with the slip rings to allow current to be directed out to the external circuit. The loop spins on the axis of rotation. The spinning force is provided by an external source of energy. For example, recall from Chapter 5 that at a hydroelectric power plant, the falling water turns the blades of a turbine connected to the electrical generator.

In Figure 1, the loop of the generator is being forced clockwise. Since the loop is moving inside the magnetic field provided by the external magnets, an electric current will be induced in the loop as described by Faraday's law. The direction of the induced current is predicted by Lenz's law. Remember that an induced current also creates an induced magnetic field around the loop. The induced magnetic field around the loop opposes the field that created it.

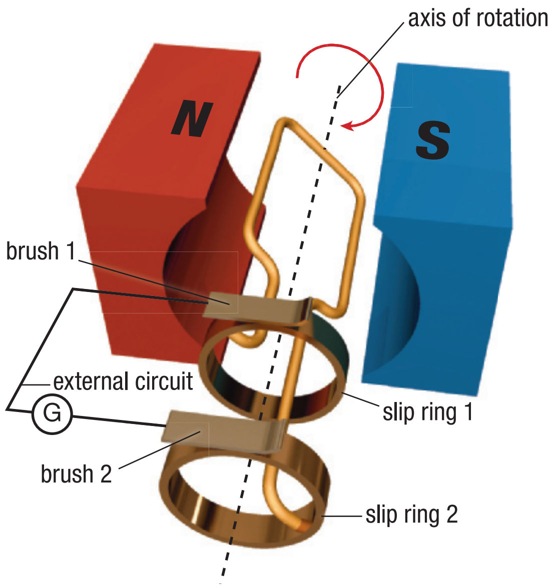


Figure 1 A single-loop AC generator

Let us examine the left part of the loop, in cross-section, closest to the north pole of the external magnet (**Figure 2**).

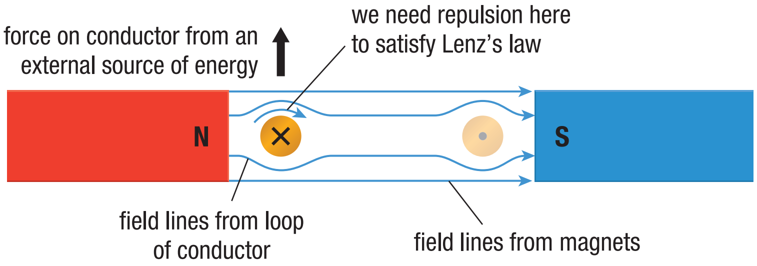

force on conductor from an external source of energy
we need repulsion here to satisfy Lenz's law
N
S
field lines from loop of conductor
field lines from magnets

Figure 2 A cross-section view of the wire loop in the generator in Figure 1. An external source of energy moves the wire upward at the left side and downward at the right side.

The magnetic field around the wire opposes the external magnetic field. This happens because the field lines at the top of the wire are pointed in the same direction as the field lines from the external magnet. Magnetic field lines pointing in the same direction result in a force of repulsion. The force on the conductor coming from an external source of energy overcomes the magnetic repulsion force between the field from the conductor and the field from the magnets. Using the right-hand rule for a straight conductor, the conventional current points into the page.

Let us now examine the part of the loop, in cross-section, closest to the south pole of the external magnet (**Figure 3**).

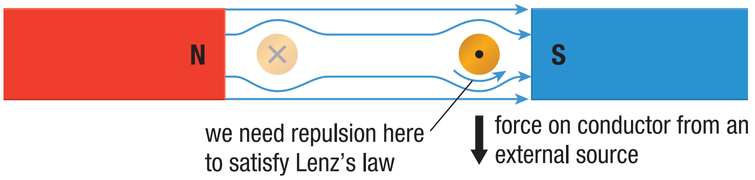

N
S
we need repulsion here to satisfy Lenz's law
force on conductor from an external source

Figure 3 A cross-section view of the wire loop in the generator in Figure 1. An external source of energy moves the wire upward at the left side and downward at the right side.

On this side of the loop, the conductor is being forced downward, and the magnetic field from the loop opposes the external magnetic field. Again the field lines from the wire point in the same direction as the field lines from the external magnet and cause repulsion. Using the right-hand rule for a straight conductor, the conventional current points out of the page.

Therefore, the rotation of the loop in a clockwise direction in the magnetic field causes a conventional current in the loop in the direction shown in **Figure 4**. In the following Tutorial, we will investigate the direction of the current in the external circuit attached to the generator shown in Figure 4.

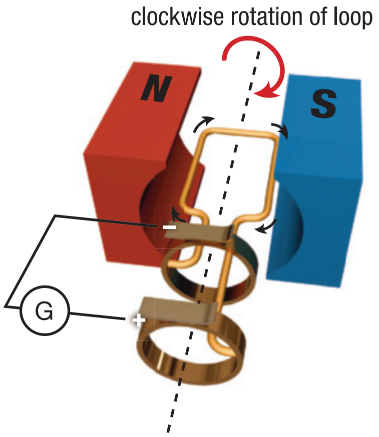

clockwise rotation of loop
N
S
–
+
G

Figure 4 The direction of the induced current is shown by the black arrows around the loop. Note the positive and negative signs on the external circuit.

Tutorial 1 Explaining the AC Generator

As the loop of an AC generator spins, a current forms in the external circuit connected to the generator. What is the direction of the current in the external circuit?

In **Figure 5**, the current in the loop heads toward slip ring 2, which contacts brush 2, and into the external circuit as shown. Since the conventional current goes into the galvanometer at the positive terminal, the galvanometer needle points to the positive side of the scale.

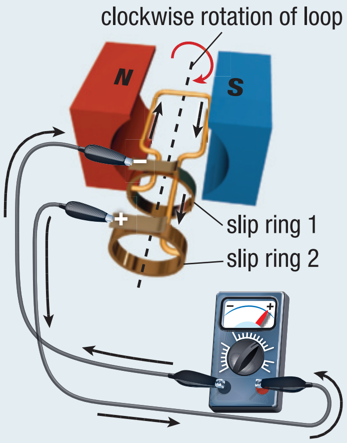


Figure 5

In addition to the factors discussed in Section 13.1, the amount of induced current also depends on the angle of the conductor in relation to the external magnetic field. The induced current is at a maximum when the plane of the loop is parallel to the external magnetic field. As the loop rotates toward 90° of rotation, the amount of current decreases. Once the loop is perpendicular to the magnets (or 90° of rotation), the current reads zero, as shown in **Figure 6**.

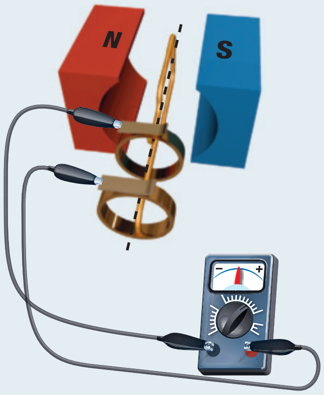


Figure 6

As the loop rotates from 90° of rotation and approaches 180°, the conventional current in the loop goes into slip ring 1. This reverses the direction of the current in the external circuit, as shown in **Figure 7**. Note that the conventional current goes into the galvanometer at the negative terminal. The galvanometer needle moves to the negative side.

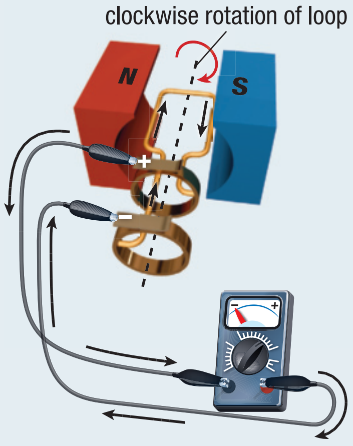


Figure 7

As the loop rotates away from 180°, the current once again decreases until it reaches zero at 270° of rotation, as shown in **Figure 8**.

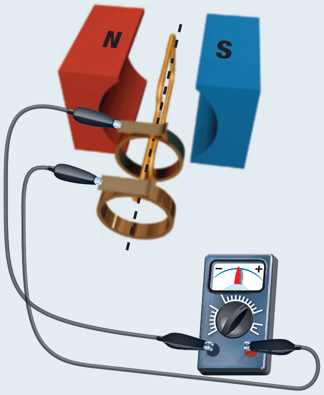


Figure 8

At this point, the current once again reverses direction and enters the external circuit at slip ring 2. This starts the whole process over again. The galvanometer readings are plotted on a graph in **Figure 9**. The rotation rate of the loop matches the frequency at which the current changes direction.

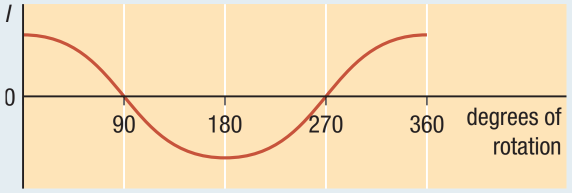


Figure 9

Mini Investigation

What Factors Affect Electricity Generation?

Skills: Planning, Performing, Observing, Communicating

SKILLS HANDBOOK **A2.1, A2.4**

Generators use coils and magnets to generate electricity. In this investigation, you will determine what factors affect the amount of current produced.

Equipment and Materials: galvanometer; 2 bar magnets; 2 coils with different number of windings; 2 alligator clip leads

1. Connect the coil with fewer windings to the galvanometer using the alligator clip leads.
2. Plan a procedure to test the factors that affect the amount of current produced.
3. Record your observations in a series of statements that are framed as follows: Changing the ___________ produced a maximum reading on the galvanometer of _______.

A. How did moving the magnet more quickly into the coil affect the amount of current? T/I

B. How did reversing the pole of the magnet inserted in the coil, while keeping the speed of the magnet going into the coil constant, affect the amount of current? T/I

C. How did using two magnets affect the amount of current? T/I

D. How did changing the number of windings in the coil affect the current? T/I

Factors Affecting Generator Output

The single-loop AC generator discussed in Tutorial 1 is useful for demonstration purposes. However, to increase the amount of current generated we could use a coiled conductor wrapped around a soft-iron armature. This increases the strength of the induced magnetic field. We could also rotate the soft-iron armature faster or use stronger external magnets. In Tutorial 2 we will look at using a coil in a generator.

Tutorial 2 Using a Coil in an AC Generator

A coil-type generator uses a coil wrapped around a soft-iron armature, as shown in **Figure 10**. This armature is rotated by an external source of energy. How does this design affect the direction of current in the external circuit?

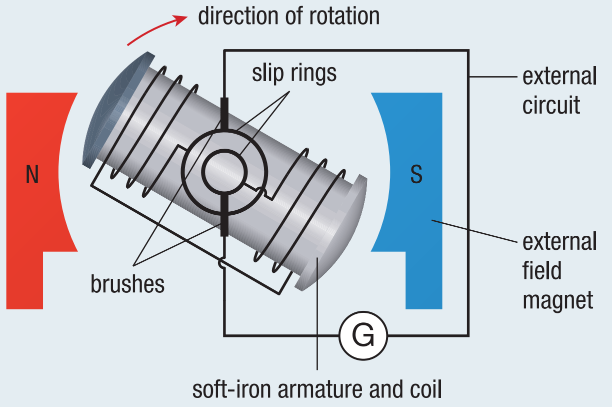


Figure 10

The rotation of the generator shown in Figure 10 is clockwise. As the shaded side of the armature moves away from the north pole of the external magnet, Lenz's law determines the left side of the armature to be a south magnetic pole. The armature is forced away from north. Thus, the induced magnetic field must oppose being pulled away by attracting with a south pole. Using the right-hand rule for a coil, the direction of the conventional current is as shown in **Figure 11**.

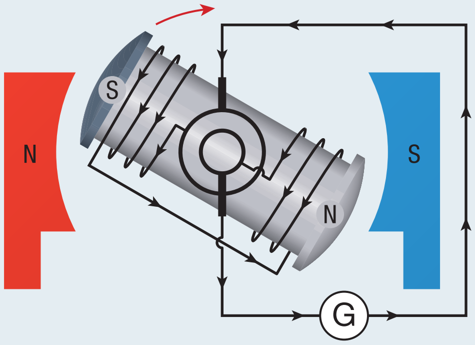


Figure 11

As the shaded side of the armature spins away from the north pole of the external field magnet, the amount of current increases to a maximum until the shaded side of the armature starts approaching the south pole of the external field magnet. The current increase can be explained by referring back to Tutorial 1. When the single loop was oriented so that it was perpendicular to the external magnetic field, the induced current was zero. When the single loop was oriented so that it was parallel to the external magnetic field, the induced current was at a maximum. The same applies whether you are using one loop or several loops. Using Lenz's law, the shaded side of the armature resists going toward south by repelling. This makes the shaded side of the armature a south pole. Using the right-hand rule, the direction of the conventional current is as shown in **Figure 12**.

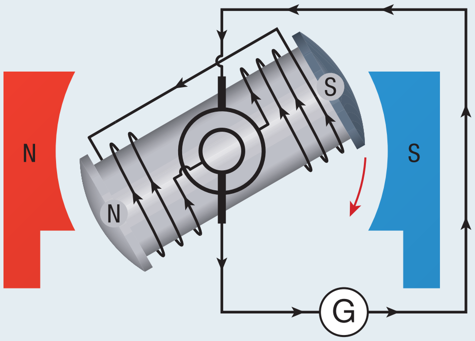


Figure 12

Now the shaded side of the armature spins away from the south pole of the external field magnet. This time Lenz's law predicts the shaded side of the armature to be north. This is because the shaded side of the armature is moving away from the south pole of the external field magnet. The shaded side of the armature must resist moving away by attracting to a north pole. The current now reverses direction as shown in **Figure 13**.

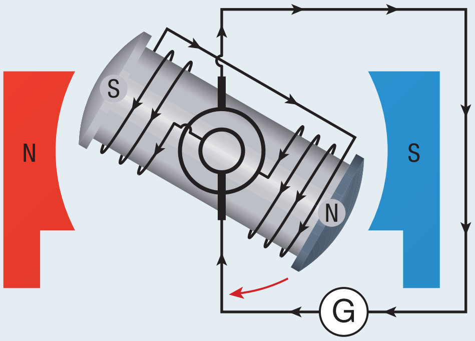


Figure 13

As the shaded side of the armature moves away from the south pole of the external field magnet, the current increases to a maximum value until the shaded side of the armature starts approaching the north pole of the external field magnet. The shaded side of the armature remains north on the side approaching north, causing repulsion. The current goes in the direction shown in **Figure 14**.

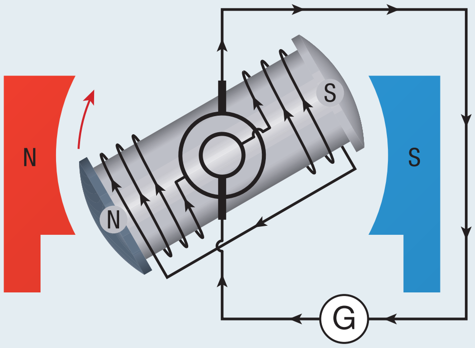


Figure 14

DC Generators

A DC generator, as shown in **Figure 15**, has the same design as a DC motor. It has a split ring commutator instead of slip rings. The split ring commutator serves to prevent the current from changing direction in the external circuit as it does in the AC generator. However, the induced current in the coil in the armature is still the same, as has been shown in the tutorials.

In the case of the DC motor, electrical energy is transferred into the motor to cause rotation or kinetic energy. In the case of a DC generator, rotation or kinetic energy (for example, from falling water, wind, or high-pressure steam) is used to turn the coil to generate electrical energy. Therefore, a generator may be considered a motor in reverse.

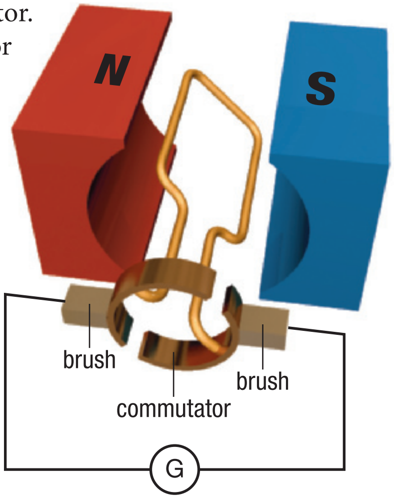


Figure 15 DC generator

Research This

Wind Turbines

Skills: Researching, Communicating, Identifying Alternatives SKILLS HANDBOOK A5.1

Wind is a renewable resource, and many different designs of wind turbines are being engineered. Some are large and able to deliver enough electrical energy to power 5000 homes. Others are smaller and can power only one home. As you learned in this section, in a generator, the rotation rate of the loop is directly related to the frequency of the alternating current. Canada's electrical grid requires a frequency of 60 Hz. Different design philosophies are put in place to achieve this.

1. Choose a wind turbine technology. You can consider large-scale land-based turbines, off-shore turbines, or some of the novel small-scale turbines for residential applications.
2. Research how the technology works. Highlight the type of turbine used, the generator used, the type of technology used to control the electricity to feed it into the grid, and where the electricity is being used or developed.

A. At what rotation rate does the wind turbine spin, and how is the electricity controlled? T/I A

B. What are the maintenance considerations? K/U T/I

C. Prepare a tri-fold pamphlet highlighting your research. T/I C A

GO TO NELSON SCIENCE

UNIT TASK **BOOKMARK**

You can apply what you have learned about electric generators to the Unit Task on page 622.

13.4 Summary

- An electric generator transforms other forms of energy into electrical energy.
- Alternating current generators are designed with loops of a conductor that spin in a magnetic field. The ends of the loops are connected to two different slip rings, allowing them to produce alternating current.
- Coiling the conductor around an armature increases the strength of the induced magnetic field, making the generator produce more current.
- Spinning the armature more quickly or using a stronger external magnetic field also increases the current produced by the generator.
- DC generators are designed like a DC motor except energy is put into spinning the coil to generate electricity rather than putting electrical energy into the motor to cause it to spin.

13.4 Questions

1. Sketch the generator shown in Figure 1 on page 599, but change the rotation to counterclockwise. Answer the following questions based on your diagram. Consider the starting angle to be 0°. T/I C
    (a) At what angle(s) relative to your starting point would you expect maximum current in the loop?
    (b) At what angle(s) relative to your starting point would you expect a zero current?
    (c) Sketch a graph of the induced current in the external circuit.
    (d) What effect would reversing the polarity of the external magnets have on the current?
2. How does the rotation rate of the loop in the generator in Figure 1 compare to the frequency of the alternating current? K/U
3. How many times per second does a generator armature rotate in North America? K/U
4. The generator in **Figure 16** is rotated counterclockwise. Determine the polarity of the magnetic field on the armature, the direction of induced current in the coil, and the direction of current in the external circuit. T/I

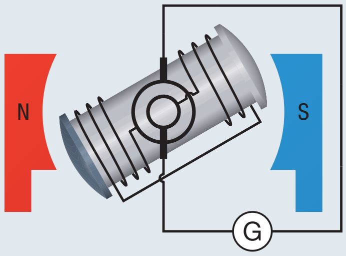


Figure 16

Transformers

13.5

The electrical devices you use every day all have different electrical energy requirements. An electric stove requires a lot of electrical energy, while an LED requires very little. Some devices require different currents and voltages. For example, a computer may require only 12 V to operate, so the voltage in your home needs to be lowered from 120 V to 12 V. Devices that are capable of raising or lowering AC voltage are called **transformers**. Transformers are used in many electronic devices to lower or raise the AC voltage to the value that the device is designed for (**Figure 1**). Adapters, such as cellphone chargers, have transformers as part of their circuitry. Adapters also contain a circuit that converts AC voltage to DC voltage.

transformer an electromagnetic device that can raise or lower voltage

Figure 1 A transformer

How Transformers Work

To understand how a transformer works, recall Faraday's ring from Section 13.1. The ring has a primary circuit and a secondary circuit. These circuits are not in physical contact, but a current in the primary circuit induces a current in the secondary circuit. According to the law of electromagnetic induction, a changing magnetic field is required to induce a current. A changing magnetic field can be produced by using alternating current. An alternating current in the primary coil is the most critical part to producing an alternating current in the secondary coil of a Faraday's ring.

Suppose that we change the number of windings in the coils on either the primary or the secondary circuit of a Faraday's ring. Would the same AC voltage be measured across both the primary circuit and the secondary circuit?

Transformers have different numbers of windings on the primary circuit compared to the secondary circuit (**Figure 2**). If the secondary circuit has fewer windings than the primary circuit, the voltage on the secondary side is less than the voltage on the primary side. Transformers that have fewer windings on the secondary circuit than the primary circuit are called **step-down transformers**. They are called step-down transformers because they lower the AC voltage by a specific amount.

If the situation is reversed and the secondary circuit has more windings, then the voltage is higher on the secondary side. Transformers that have more windings on the secondary circuit than on the primary circuit are called **step-up transformers**. They are called step-up transformers because they increase the AC voltage by a specific amount. So we can lower or raise the voltage in the secondary circuit just by changing the number of windings.

step-down transformer a transformer with fewer secondary windings than primary windings

step-up transformer a transformer with more secondary windings than primary windings

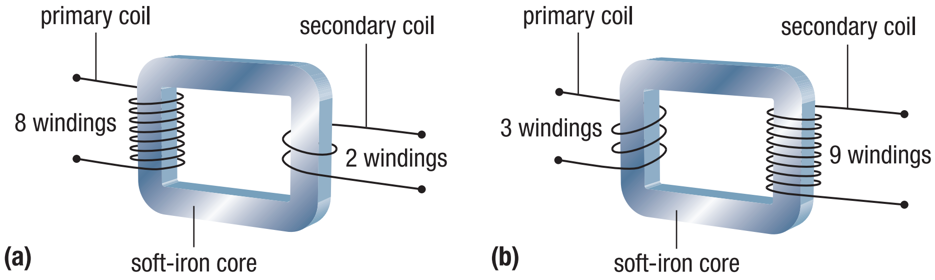


Figure 2 (a) A step-down transformer has fewer windings on the secondary coil than on the primary coil. (b) A step-up transformer has more windings on the secondary coil than on the primary coil.

Mini **Investigation**

Observing Transformers at Work

Skills: Performing, Observing, Analyzing

SKILLS HANDBOOK **A1.2, A2.1, A3**

In this investigation, you will observe how a transformer works with direct current and alternating current.

Equipment and Materials: variable AC/DC power supply; 2 AC/DC multimeters with probes; transformer with different number of windings on primary and secondary coils; 2 alligator clip leads

1. Set up a circuit with the variable DC power supply connected to the transformer using the leads as shown in **Figure 3**. Make sure that the power supply is off.

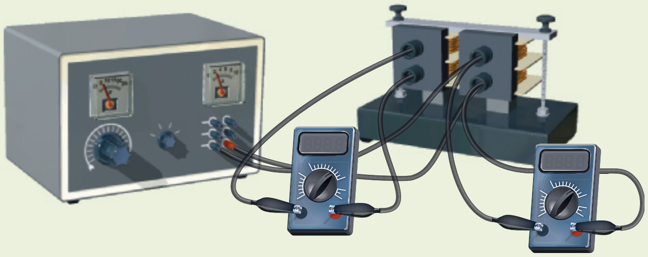


Figure 3

2. With the power supply off, set to the voltage specified by your teacher.
3. Set the multimeters to measure DC voltage, and connect one multimeter to the primary coil and the other multimeter to the secondary coil.
4. While watching the display on the multimeters, turn on the DC power supply. Only turn on the power supply when instructed to do so by your teacher. Record your observations. Turn off the power supply and record your observations.
5. Disconnect the transformer from the DC power supply and connect the alligator clip leads to the AC connection. Set your multimeters to measure AC voltages and repeat Step 4.

A. How effectively did the transformer work with DC? T/I C

B. How did the AC voltage on the primary coil compare to the AC voltage on the secondary coil? T/I

C. Is your transformer a step-up or a step-down transformer? T/I

Conservation of Energy in Transformers

Transformers must obey the law of conservation of energy. Therefore, the energy going into the primary coil must equal the energy coming out of the secondary coil if there are no energy losses. Recall from Section 5.5 that the change in energy is expressed as $\Delta E = P\Delta t$. Power in an electrical circuit is expressed as the product of voltage and current, or $P = VI$. Using the energy and power equations, we can express the law of conservation of energy as shown below. (The subscript "p" represents primary and the subscript "s" represents secondary.)

$$\Delta E_p = \Delta E_s$$

$$P_p t = P_s t$$

$$P_p = P_s$$

substitute $P = VI$

$$V_p I_p = V_s I_s$$

In the above expression, you can see that both sides of the equation have the same terms. Whatever amount of energy goes into the primary coil must come out of the secondary coil. If the number of windings is the same on both sides, the voltages and currents are the same.

In a step-down transformer, the voltage on the secondary coil, V_s, is lower than the voltage on the primary coil, V_p. So, from the equation above and the law of conservation of energy, we can deduce that the current on the secondary side, I_s, must be greater than the current on the primary side, I_p. In a step-up transformer, the voltage on the secondary coil, V_s, is higher than the voltage on the primary coil, V_p. To comply with the law of conservation of energy, the current in the secondary side, I_s, must be less than the current on the primary side, I_p. Therefore, the voltage and current are inversely proportional. For example, if voltage is doubled, current is halved, and vice versa.

Transformer Equations

From the law of conservation of energy we derived the following equation:

$$V_pI_p = V_sI_s$$

Grouping I and V together gives

$$\frac{V_p}{V_s} = \frac{I_s}{I_p} \text{ (equation 1)}$$

The voltage in the coil is directly proportional to the number of windings, so

$$\frac{V_p}{V_s} = \frac{N_p}{N_s} \text{ (equation 2)}$$

where N_p is the number of windings on the primary coil and N_s is the number of windings on the secondary coil. We can also express current in a transformer with respect to the number of windings by combining equations 1 and 2.

$$\frac{V_p}{V_s} = \frac{I_s}{I_p} \quad \text{and} \quad \frac{V_p}{V_s} = \frac{N_p}{N_s}$$

Thus,

$$\frac{I_s}{I_p} = \frac{N_p}{N_s}$$

So the current is inversely proportional to the number of windings. We will use these equations in the following Tutorials.

LEARNING **TIP**

Transformer Equations

You can remember one equation:

$$\frac{V_p}{V_s} = \frac{I_s}{I_p} = \frac{N_p}{N_s}$$

LEARNING **TIP**

Significant Digits and Windings

The number of windings is an exact number and does not limit the number of significant digits in a calculation.

Tutorial **1** Voltage in a Transformer

We will use the equation $\frac{V_p}{V_s} = \frac{N_p}{N_s}$ to solve a problem involving voltage in a step-down transformer.

Sample Problem 1

A step-down transformer used in an adapter for a laptop has a primary voltage of 120 V. There are 250 windings in the primary coil and 25 windings in the secondary coil. Calculate the voltage in the secondary coil.

Given: $V_p = 120$ V; $N_p = 250$; $N_s = 25$

Required: V_s

Analysis: $\frac{V_p}{V_s} = \frac{N_p}{N_s}$

Rearrange the equation as follows, allowing for easier subsequent rearranging:

$$V_pN_s = V_sN_p$$

Solve for V_s:

$$V_s = \frac{V_pN_s}{N_p}$$

Solution: $V_s = \frac{V_pN_s}{N_p}$

$$= \frac{(120\text{ V})(25)}{250}$$

$$V_s = 12\text{ V}$$

Statement: The voltage in the secondary coil is 12 V.

Practice

1. A step-down transformer has a primary voltage of 240 V. The number of windings in the primary coil is 550 and the number of windings in the secondary coil is 110. Determine the voltage of the secondary coil. T/I [ans: 48 V]
2. A step-up transformer has a primary voltage of 31.0 V. The number of windings in the primary coil is 211 and the number of windings in the secondary coil is 844. Determine the voltage of the secondary coil. T/I [ans: 124 V]

Tutorial 2 Current in a Transformer

We will use the equation $\frac{I_s}{I_p} = \frac{V_p}{V_s}$ to solve a problem involving current in a step-down transformer.

Sample Problem 1

A step-down transformer used in the adapter for a cellphone charger has a primary voltage of 120 V and a secondary voltage of 5.0 V. The current in the primary coil is 0.10 A. Calculate the current in the secondary coil.

Given: $V_p = 120$ V; $V_s = 5.0$ V; $I_p = 0.10$ A

Required: I_s

Analysis: $\frac{I_s}{I_p} = \frac{V_p}{V_s}$

Solve for I_s:

$$I_s = \frac{V_p I_p}{V_s}$$

Solution:
$$\begin{aligned} I_s &= \frac{V_p I_p}{V_s} \\ &= \frac{(120\text{ V})(0.10\text{ A})}{5.0\text{ V}} \\ I_s &= 2.4\text{ A} \end{aligned}$$

Statement: The current in the secondary coil is 2.4 A.

Practice

1. A step-down transformer has a primary voltage of 240 V and a secondary voltage of 12 V. The primary current is 0.15 A. Determine the current in the secondary coil. T/I [ans: 3.0 A]
2. A step-up transformer has a primary voltage of 620 V and a secondary voltage of 12 000 V. The current in the secondary coil is 1.3 A. Determine the current in the primary coil. T/I [ans: 25 A]

Transformer Efficiency

The law of conservation of energy states that no energy is lost, but in practice some energy is converted into unusable energy. In a transformer, some of the energy is transformed into unusable thermal energy in the coils, as well as sound energy. Some transformers make a noticeable hum because the transformer core is vibrating. Typically, transformers are better than 90 % efficient. To maximize efficiency, the coils are made from conductors with low resistance, such as copper, and the core is rectangular to ensure that the magnetic field lines go through both coils effectively.

13.5 Summary

- A transformer raises or lowers AC voltage. It consists of a primary coil, a secondary coil, and a soft-iron core.
- Step-down transformers have fewer secondary windings than primary windings and decrease the voltage in the secondary coil.
- Step-up transformers have more secondary windings than primary windings and increase the voltage in the secondary coil.
- The voltage is directly proportional to the number of windings.
- The current is inversely proportional to the number of windings.
- The equations related to transformers are

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}, \qquad \frac{I_s}{I_p} = \frac{N_p}{N_s}, \qquad \text{and} \qquad \frac{I_s}{I_p} = \frac{V_p}{V_s}.$$

13.5 Questions

1. Why do transformers need an alternating current to operate continuously? K/U
2. How can you tell the difference between a step-up and a step-down transformer? K/U
3. A student is discussing transformers and states that the voltage and the current both increase in a step-up transformer. Explain why this is not possible. K/U
4. Suppose that you increase the number of windings on the secondary coil compared to the primary coil. What would you expect the effect on voltage and current to be? K/U
5. Would a device that has the same number of windings on both the primary coil and the secondary coil be classified as a transformer? Explain. K/U
6. Are transformers 100 % efficient? Explain. K/U
7. The number of windings on the primary coil of a transformer is 1.5 times greater than on the secondary coil. The primary coil has a current of 3.0 A and a voltage of 12.0 V. Determine the voltage and current on the secondary coil. T/I
8. Copy **Table 1** into your notebook and find the missing values. T/I

Table 1

Transformer	V_p	V_s	N_p	N_s	I_p	I_s	Step-up or step-down?
1	12 V	120 V	100		1.2 A		
2		110 V	600	100	150 mA		
3	30 V		120		0.28 A	1.68 A	

9. An AC adapter for a laptop has a transformer inside it. It will take a 120 V AC and step it down to 15.0 V AC. Determine the ratio of primary windings to secondary windings in the transformer. T/I

13.6 Power Plants and the Electrical Grid

In Section 13.3, the historical competition between the use of AC and DC electricity was discussed. Efficiency was one of the main reasons why AC electricity won over DC. But why is AC more efficient? To answer that question, we must first examine the transmission of electrical energy along a conductor.

Transmission Efficiency and Current

Generators at today's large-scale power plants can produce huge amounts of power. A significant amount of this power can be lost due to thermal energy losses as large currents pass through the transmission wires. To determine how much power is lost in a transmission wire, we can use the power equation $P = VI$. To solve for lost power, we can derive a new power equation using Ohm's law to substitute for V:

$$P = VI$$

$$P = (IR)(I)$$

$$P = I^2R$$

This equation can be used to calculate the amount of power lost in the wire due to thermal energy losses.

Assume that a generator produces 300 MW (3×10^8 W) of power at a current of 30 kA, which travels through a transmission wire with a resistance of 0.1 Ω. Using the new power equation we find

$$\begin{aligned} P &= I^2R \\ &= (30\ \text{kA})^2(0.1\ \Omega) \\ &= (30\,000\ \text{A})^2(0.1\ \Omega) \\ &= 9 \times 10^7\ \text{W} \\ P &= 90\ \text{MW} \end{aligned}$$

So 90 MW of power is transformed to unusable thermal energy. This represents a loss of 30 %.

Note that the lost power is proportional to the square of the current, so if we could lower the current going through the wire, there would be much less power lost. Fortunately, a transformer can lower the current, increase the voltage, and keep the same power. By using a transformer at a power plant we step up the voltage. Suppose that we increase the voltage to 100 kV. This lowers the current to 3 kA. Repeating the calculation, we find

$$\begin{aligned} P &= I^2R \\ &= (3\ \text{kA})^2(0.1\ \Omega) \\ &= (3000\ \text{A})^2(0.1\ \Omega) \\ &= 9 \times 10^5\ \text{W} \\ P &= 0.9\ \text{MW} \end{aligned}$$

This represents a loss of 0.3 %, which is a significant improvement. This is the main reason why we generate AC electricity at power plants. Transformers will only work with AC electricity. Without the transformer, the amount of power lost in transmission would be impractical.

The Electrical Power Grid

The electrical power grid is a giant circuit composed of many parallel circuits fed by the electrical energy of a number of power plants. The grid transmits AC power using transformers that step up and step down the voltage where necessary (**Figure 1**).

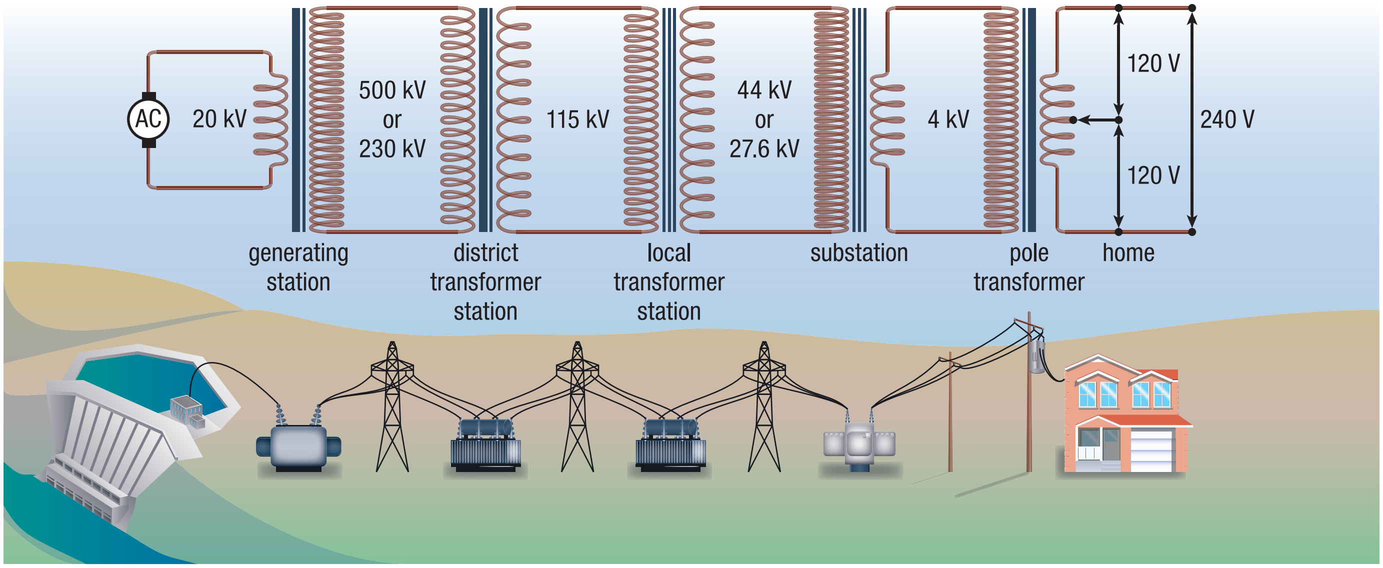


Figure 1 The step-up and step-down transformers used in a typical electrical grid

In Figure 1, the generator produces 20 kV of AC, which is immediately increased to 230 kV or higher to minimize energy loss. The electricity is then sent along power transmission lines suspended high above the ground supported by towers. If the voltages were higher, then the electricity could discharge through the air and into the ground. The electricity is gradually decreased in voltage at a district transformer station, a local transformer station, a substation (**Figure 2**), and then a pole or ground transformer in your neighbourhood (**Figure 3**).

The electrical power grid is monitored, and energy is fed into the grid on demand. If more energy is needed, and there is the capacity, then more is fed in. Power plants only generate the amount of electricity that is needed because electrical energy cannot easily be stored. If more is generated than needed, it is sold to other electrical grids farther away. If more electrical energy is needed and we do not have the capacity, then we purchase it from other grids at a higher cost. On some summer days in Ontario, when demand is high, we may use more electrical energy than the power plants are capable of generating. So we purchase electricity from the United States in order to meet the increased need.

The electrical grid needs maintenance. As the grid ages, continued repair and replacement are needed and the costs are passed along to the consumer. If you look at your electricity bill, you will find that there are costs listed for the amount of electricity used and its delivery. The delivery fee is collected to maintain the grid.

Figure 2 Transformers at this substation step down the voltage so that it is low enough to be transmitted to neighbourhoods.

4499
NON PCB
WARNING
NOTICE

Figure 3 This residential transformer steps down the voltage to 240 V for use in your home.

Commercial AC Generators

The generators used in power plants contain multiple coils and armatures. The field magnets are not permanent magnets because it is difficult to make a strong enough magnet. Also, permanent magnets lose their magnetism over time because of the strong magnetic fields in the coils. So, instead, electromagnets are used. To increase the strength of an electromagnet, you increase the current. Where does the electrical energy come from to power the electromagnets? In some cases, it comes from the AC generator itself. In other cases, the AC generator has a DC generator that uses permanent magnets. The DC generator uses a source of energy (such as falling water) to generate electrical energy, which is then used to power the electromagnets of the AC generator. The AC generator uses a source of energy (such as falling water) along with the DC generator to generate AC electricity. **Figure 4** shows cross-sections of a large-scale generator and a hydroelectric power plant.

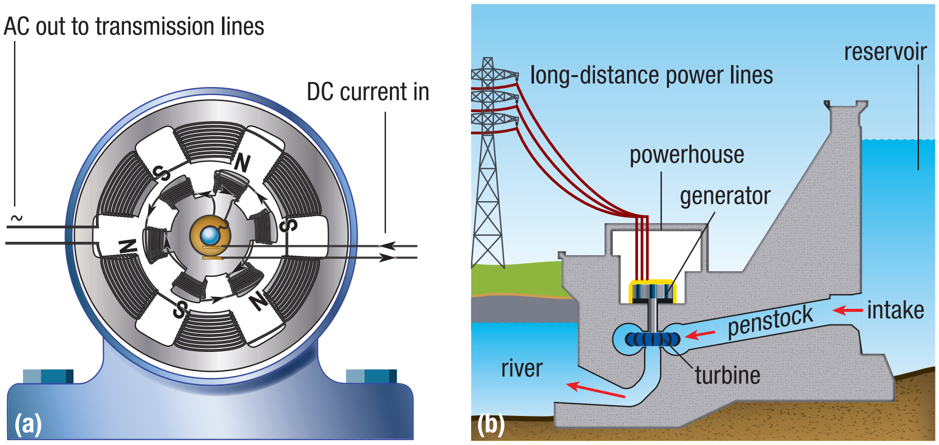


Figure 4 (a) Cross-section of a large generator (b) Cross-section of a hydroelectric power plant

CAREER LINK

Power technicians construct and maintain generation, transmission, and distribution stations. To learn more about becoming a power technician,

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The rotation speed of a generator must be managed to maintain the desired frequency of 60 Hz. As electricity demand increases, more current is drawn into the grid and it becomes more difficult to turn the generator. You can increase the turning force of the turbine rotating the generator shaft. If this cannot be done, you can decrease the strength of the electromagnets inside the generator. This lowers the voltage. It is for this reason that the voltages continually fluctuate a small amount throughout the day. The voltages are required to be relatively constant, however, and can only fluctuate within a regulated amount.

13.6 Summary

- Transmission of AC electricity requires the use of transformers to minimize losses.
- Step-up transformers at the power plant are used to increase the voltage and decrease the current for transmission.
- Step-down transformers are used throughout the grid to bring voltages down to levels that can be used in homes.
- Commercial generators have multiple armatures and coils using electromagnets to generate AC electricity.

13.6 Questions

1. Describe the main reason why AC power generation was chosen over DC power generation. K/U C
2. Determine the power loss in each of the following. Express your answer as a percent. T/I
   (a) A 200 MW power plant delivers a current of 2 kA in a 10 Ω wire.
   (b) A 200 MW power plant delivers a current of 200 A in a 10 Ω wire.
   (c) A 10 MW wind turbine delivers a current of 3000 A in a 0.50 Ω wire.
3. Why is electrical energy generated on demand? K/U C
4. What is the difference between the electrical generators you learned about in Section 13.4 and the commercial generators discussed in this section? C A
5. Look at Figure 1 on page 611. The pole transformer has a secondary coil with a connection point in the middle of the coil as well as at the ends. Why do you suppose that is the case? K/U
6. Commercial generators were described as using electromagnets which are sometimes powered by the generator itself. Would it be possible to just let the generator power itself without the need for an external energy source? Explain your answer. K/U

CHAPTER 13 Investigations

Investigation 13.2.1 OBSERVATIONAL STUDY

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Investigating Electromagnetic Induction

The generation of electrical energy uses the principle of electromagnetic induction. What factors affect the strength of the induced current and make electricity generation more effective?

Purpose

To change the magnetic field and observe the direction of induced current

Equipment and Materials

- galvanometer (or ammeter)
- 2 bar magnets
- 2 different coils of wire (one with more windings than the other)
- 2 alligator clip leads

Procedure

1. Connect the 2 alligator clip leads to the terminals of one coil of wire and the galvanometer terminals. Make note of the direction in which the coil is wound.
2. Gently move the north pole of one magnet into the coil and observe the direction of the deflection of the galvanometer needle. Using the conventional current convention, describe the direction of current in the coil.
3. Move the magnet into the coil quickly, and again observe the galvanometer. Using the conventional current convention, describe the direction of current in the coil.
4. Repeat Steps 2 and 3, but this time pull the magnet out of the coil.
5. Repeat Steps 2 and 3, but this time move the south pole of the magnet into the coil.
6. Repeat Steps 2 and 3 using two magnets (with poles aligned to increase the strength of the magnetic field).
7. Repeat Steps 2 and 3 by moving the coil in the direction of the magnet. The magnet should be aligned with the core of the coil.
8. Repeat Steps 2 and 3 using the other coil (with a different number of windings).

Analyze and Evaluate

(a) Identify the manipulated and responding variables when investigating the speed of the moving magnet versus current. T/I

(b) Make a statement about the direction of conventional current when moving the magnet into the coil compared with moving it out of the coil. T/I C

(c) Make a statement about the magnitude of the conventional current when the speed of the magnet changes. T/I C

(d) Increasing the speed of the coil increases its kinetic energy. How does the current in the coil ensure that the law of conservation of energy is obeyed? T/I

(e) How does changing the magnetic pole affect the direction of conventional current? T/I

(f) Does moving the coil versus moving the magnet change the results? Explain. T/I

(g) How did using the second coil affect your results? Explain. T/I

(h) From your results in Step 2, use the right-hand rule for a coil to determine the magnetic pole at the entrance point of the magnet. Are the results consistent with Lenz's law? Describe how the results are or are not consistent. T/I C

Apply and Extend

(i) What would happen if you rotated a magnet inside the coil? A

(j) Does the orientation of the magnet change the amount of current? Explain. T/I

(k) The coil uses an insulated conductor for the windings. What effect would using a bare conductor for the windings have? A

CHAPTER 13 SUMMARY

Summary Questions

1. Create a study guide based on the points in the margin on page 586. For each point, create three or four sub-points that provide further information, relevant examples, explanatory diagrams, or general equations.
2. Look back at the Starting Points questions on page 586. Answer these questions using what you have learned in this chapter. Compare your latest answers with those that you wrote at the beginning of the chapter. How has your understanding changed during the study of this chapter? Note how your answers have changed.

Vocabulary

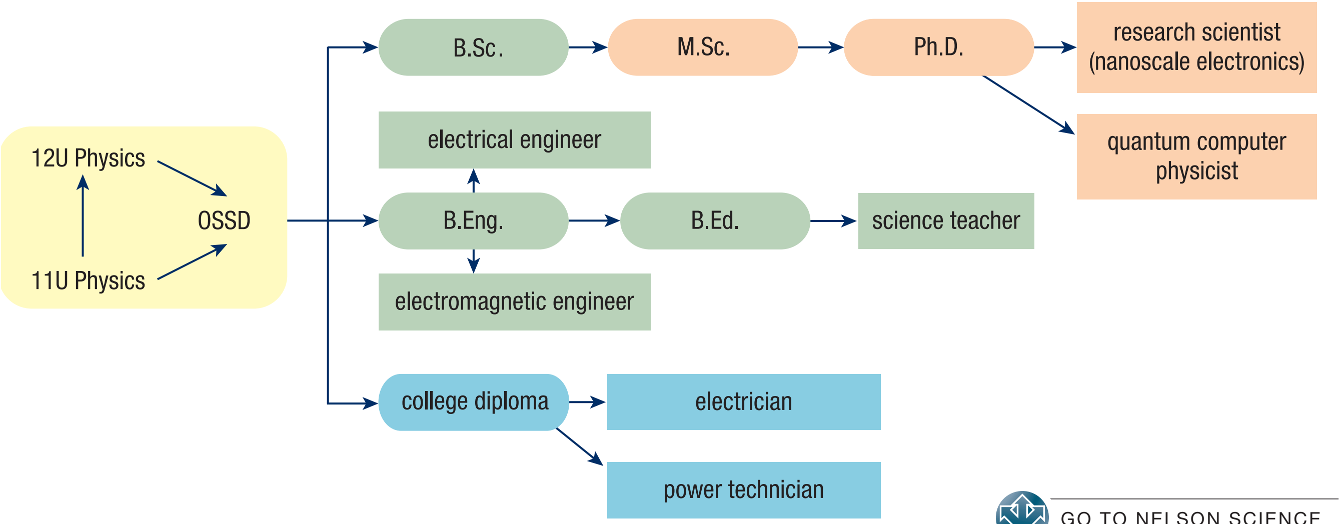
electromagnetic induction (p. 588)
law of electromagnetic induction (p. 588)
Lenz's law (p. 593)
alternating current (p. 595)
electric generator (p. 599)
transformer (p. 605)
step-down transformer (p. 605)
step-up transformer (p. 605)

CAREER PATHWAYS

SKILLS HANDBOOK A7

Grade 11 Physics can lead to a wide range of careers. Some require a college diploma or a bachelor of science degree. Others require specialized or postgraduate degrees. This graphic organizer shows a few pathways to careers related to topics covered in this chapter.

1. Select two careers related to Electromagnetic Induction that you find interesting. Research the educational pathways that you would need to follow to pursue these careers. What is involved in the required educational program? Prepare a brief report of your findings.
2. For one of the two careers that you chose above, describe the career, main duties and responsibilities, working conditions, and settings. Outline how the career benefits society and the environment.



12U Physics
11U Physics
OSSD
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M.Sc.
Ph.D.
research scientist (nanoscale electronics)
quantum computer physicist
electrical engineer
B.Eng.
B.Ed.
science teacher
electromagnetic engineer
college diploma
electrician
power technician

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CHAPTER 13 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. In Faraday's ring, which of the following actions causes electromagnetic induction in the secondary coil? (13.1) K/U
   (a) turning the direct current on in the primary circuit
   (b) turning the direct current off in the primary circuit
   (c) turning the direct current on and off repeatedly in the primary circuit
   (d) all of the above
2. Which of the following descriptions is consistent with Lenz's law? (13.2) K/U
   (a) If a north magnetic pole is moved into a coil, the same side of the coil is now a south magnetic pole.
   (b) If a north magnetic pole is moved out of a coil, the same side of the coil is now a south magnetic pole.
   (c) If a south magnetic pole is moved into a coil, the opposite side of the coil is now a south magnetic pole.
   (d) If a south magnetic pole is moved out of a coil, the opposite side of the coil is now a north magnetic pole.
3. Alternating current has which of the following properties? (13.3) K/U
   (a) Electrons travel in one direction only.
   (b) Voltage and current rise and fall periodically.
   (c) Electrons travel from the distribution panel to your room to operate your lamp.
   (d) Voltage and current remain constant.
4. Which of the following statements is true about an AC generator? (13.4) K/U
   (a) It contains a split ring commutator and brushes.
   (b) Its spin rate is independent of the frequency of electricity generated.
   (c) It contains two different slip rings and brushes.
   (d) It produces maximum current when the coils of wire are perpendicular to the external magnetic field.
5. Which of the following correctly describes a step-up transformer? (13.5) K/U
   (a) The number of windings on the primary coil is greater than the number of windings on the secondary coil.
   (b) The current in the primary coil is less than the current in the secondary coil.
   (c) The voltage on the primary coil is less than the voltage on the secondary coil.
   (d) The ratio of the number of primary windings to the number of secondary windings is greater than one.
6. Which of the following correctly describes a step-down transformer? (13.5) K/U
   (a) The number of windings on the secondary coil is greater than the number of windings on the primary coil.
   (b) The current in the secondary coil is greater than the current in the primary coil.
   (c) The voltage on the secondary coil is greater than the voltage on the primary coil.
   (d) The ratio of the number of primary windings to the number of secondary windings is less than one.
7. Which of the following descriptions would provide the most efficient electrical energy transmission? (13.6) K/U
   (a) low-voltage and high-current DC
   (b) high-voltage and low-current AC
   (c) low-voltage and high-current AC
   (d) high-voltage and high-current AC

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

8. A magnetic field with a larger change in magnitude induces less current in a conductor than a magnetic field with a smaller change in magnitude. (13.1) K/U
9. The magnetic field induced in a coil always aligns exactly with the magnetic field that produced it. (13.2) K/U
10. A fuse has a metal strip in it that heats up and melts when too much current is drawn through it, and then it needs to be replaced. (13.3) K/U
11. The majority of devices used in North American homes require 240 V. (13.3) K/U
12. AC generators in North America produce electricity with a frequency of 60 Hz. (13.4) K/U
13. A step-up transformer has more windings on the secondary coil than on the primary coil. (13.5) K/U
14. In a step-up transformer both the current and the potential difference are increased in the secondary circuit. (13.5) K/U
15. The power lost in transmission is proportional to the square of the current. (13.6) K/U

To do an online self-quiz,
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CHAPTER 13 REVIEW

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

Knowledge

For each question, select the best answer from the four alternatives.

1. Which of the following determines the amount of current produced in a conductor by a changing magnetic field? (13.1) K/U
   (a) the rate of change of the magnetic field
   (b) the strength of the magnetic field
   (c) coiling the conductor
   (d) all of the above
2. Which of the following materials would work best for a pot used on an induction cooker? (13.1) K/U
   (a) aluminum
   (b) glass
   (c) iron
   (d) plastic
3. A metal detector relies on an induced current in the metal to be detected. Why is the induced current necessary? (13.1) K/U
   (a) The induced current creates a magnetic field that is detected.
   (b) The induced current is directly detected by an ammeter in the metal detector.
   (c) The induced current creates a vibration due to the moving electrons that is detected.
   (d) The induced current is not necessary.
4. The induced magnetic field in a coil caused by an external magnetic field will always do which of the following? (13.2) K/U
   (a) repel the external magnetic field
   (b) attract the external magnetic field
   (c) oppose the external magnetic field
   (d) support the external magnetic field
5. Which of the following devices most likely uses alternating current? (13.3) K/U
   (a) a computer
   (b) a calculator
   (c) a light bulb in your home
   (d) an LCD television
6. Which of the following safety systems can be used only once? (13.3) K/U
   (a) fuses
   (b) circuit breakers
   (c) ground fault circuit interrupters
   (d) arc fault circuit interrupters
7. For a single-loop AC electric generator, the current produced is zero when the plane of the loop is at which angles relative to the magnetic field? (13.4) K/U
   (a) 0° and 180°
   (b) 45° and 135°
   (c) 90° and 270°
   (d) 90° and 180°
8. Which of the following transformer ratios, $\frac{N_p}{N_s}$, will produce the most current in the secondary circuit? (13.5) K/U
   (a) $\frac{2}{5}$
   (b) $\frac{3}{7}$
   (c) $\frac{6}{5}$
   (d) $\frac{9}{4}$
9. For a given amount of power and transmission line resistance, at which of the following voltages should a power plant transmit electricity in order to minimize the amount of power lost? (13.6) K/U
   (a) 20 V
   (b) 12 kV
   (c) 250 kV
   (d) 500 V

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

10. Increasing the number of loops in a coil decreases the amount of current induced by a changing magnetic field. (13.1) K/U
11. A rapidly changing magnetic field induces more current in a conductor than a slowly changing magnetic field. (13.1) K/U
12. When a magnetic field induces a current in a coil, the electric current produces a magnetic field that opposes the change that produced it. (13.2) K/U
13. Circuit breakers are devices that prevent sparking or arcing that could cause a fire. (13.3) K/U
14. Most homes in North America use direct current. (13.3) K/U
15. Coils are used in AC generators to increase the amount of electricity produced. (13.4) K/U
16. A DC generator has the same design as a DC motor, and can be considered a motor in reverse. (13.4) K/U
17. Transformers can only operate using direct current. (13.5) K/U

Understanding

18. Coil A has 50 windings, and coil B has 30 windings. If they are both placed in a changing magnetic field and positioned accordingly, which coil will induce more current? (13.1) K/U

19. Coil A has 100 windings, and coil B has 85 windings. How many more windings should be added to coil B so that it will generate twice the amount of electricity that coil A does in a changing magnetic field? (13.1) K/U T/I

20. **Figure 1** shows a bar magnet being dropped down a long coil. (13.2) T/I
    (a) In which direction does the induced magnetic field of the coil point?
    (b) In which direction does current move through the coil?

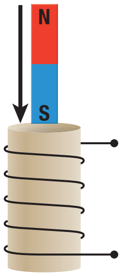

Figure 1

21. **Figure 2** shows a bar magnet being dropped down a long coil. (13.2) T/I
    (a) In which direction does the induced magnetic field of the coil point?
    (b) In which direction does current move through the coil?

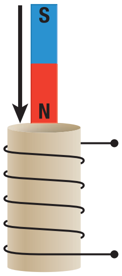

Figure 2

22. A house has a hot tub plugged into an outdoor outlet. Which safety device is most likely used with the outlet to prevent any electrical accidents? (13.3) K/U

23. A family has moved into an old house where the wiring may be deteriorating. What safety device should be installed to help prevent any fires or electrical damage while waiting for a certified electrician to change the wiring in the house? (13.3) K/U

24. For the single-loop AC generator in **Figure 3**, the direction the loop is spinning is shown. In which direction is the conventional current travelling, and is it at a maximum, zero, or neither? (13.4) T/I C

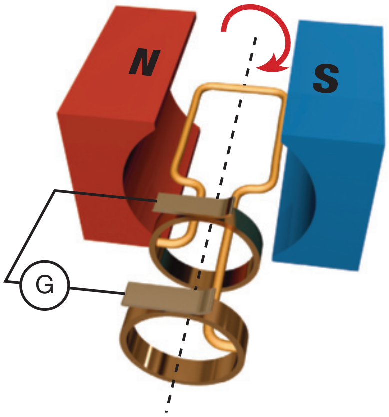

Figure 3

25. For the single-loop AC generator in **Figure 4**, the current is shown. In which direction is the loop spinning, and is the current at a maximum, zero, or neither? (13.4) T/I C

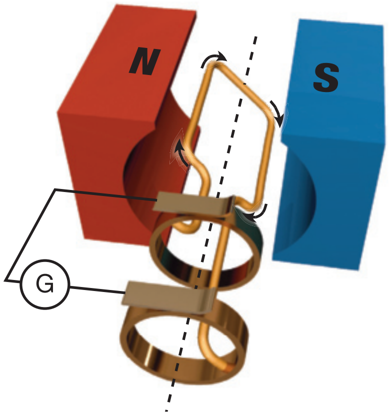

Figure 4

26. Is the transformer in **Figure 5** a step-up or a step-down transformer? (13.5) K/U

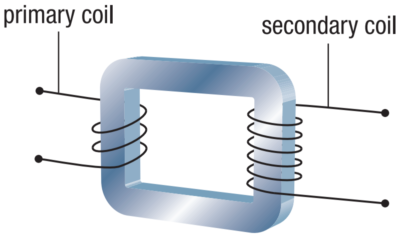

Figure 5

27. If the primary circuit of a transformer has 50 coils, how many coils should be in the secondary circuit to create a
    (a) step-up transformer?
    (b) step-down transformer? (13.5) K/U
28. If the secondary circuit of a transformer has 100 coils, how many coils should be in the primary circuit to create a
    (a) step-up transformer?
    (b) step-down transformer? (13.5) K/U
29. The primary circuit in a transformer delivers 5 A of current at 200 V. The secondary circuit delivers 10 A of current. (13.5) T/I
    (a) What is the voltage of the secondary circuit?
    (b) What is the ratio of the number of windings of the primary circuit to the number of windings of the secondary circuit?
30. The primary circuit in a transformer has 200 coils and a potential difference of 3.0×10^2 V. The secondary circuit has 300 coils. (13.5) T/I
    (a) What is the voltage of the secondary circuit?
    (b) What is the ratio of the current in the primary circuit to the current in the secondary circuit?
31. The primary circuit in a transformer has 120 coils and a potential difference of 60 V. The secondary circuit has 160 coils and a current of 5.0 A. (13.5) T/I
    (a) What is the voltage of the secondary circuit?
    (b) What is the current of the primary circuit?
32. The primary circuit of a transformer has 60 coils and 8.0 A of current. The secondary circuit has 12 A of current and a potential difference of 20 V. (13.5) T/I
    (a) What is the voltage of the primary circuit?
    (b) How many coils does the secondary circuit have?
33. The primary circuit of a transformer has a current of 5.0 A and a potential difference of 60.0 V. The secondary circuit has 120 coils and a potential difference of 25 V. (13.5) T/I
    (a) How many coils are in the primary circuit?
    (b) What is the current in the secondary circuit?
34. A power plant produces 1500 MW of power at a potential difference of 20.0 kV. How much current is produced? (13.6) T/I
35. A hydroelectric dam produces 8.0×10^2 MW of power at a current of 15 kA. What is the electric potential difference? (13.6) T/I
36. A solar plant produces electricity that is stepped up to a voltage of 150 kV at a current of 40.0 A. How much power does the solar plant produce? (13.6) T/I
37. (a) A power plant produces power at a current of 40.0 kA. If the resistance in the transmission wire is 0.30 Ω, what is the total power loss due to transmission through the wire?
    (b) The same power plant uses a transformer to step up the voltage and transmit the current at 2.0 kA. If the total resistance in the transmission wire is the same, what is the total power loss due to transmission through the wire? Assume that there is no loss of power in the step-up transformer. (13.6) T/I
38. A power plant produces 5.0×10^2 MW of power that is transmitted at a current of 20.0 kA. If the resistance in the transmission wire is 0.20 Ω, what percentage of power is lost in the transmission line? (13.6) T/I
39. A coal-fired power plant produces 2300 MW of power that is transmitted at a current of 4.0 kA. If there is a 0.50 % loss of power from transmission, what is the total resistance in the transmission wire? (13.6) T/I
40. A nuclear power plant transmits 6.0 kA through a transmission line with a resistance of 0.50 Ω. If there is a 0.70 % loss of power due to transmission, how much power does the nuclear plant generate? (13.6) T/I

Analysis and Application

41. In **Figure 6**, a small coil is placed inside a larger coil and a current is directed through the small coil in the direction shown. (13.1, 13.2) T/I
    (a) What is the direction of the magnetic field of the small coil?
    (b) What is the direction of the magnetic field induced in the large coil by the current in the small coil?
    (c) What is the direction of the current induced in the large coil?

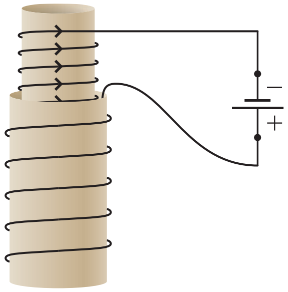

Figure 6

42. In **Figure 7**, a small coil is placed inside a larger coil and a current is directed through the large coil in the direction shown. (13.1, 13.2) T/I
   (a) What is the direction of the current in the small coil induced by the magnetic field of the small coil?
   (b) What is the direction of the magnetic field induced by the current in the large coil?
   (c) What is the direction of the magnetic field induced by the small coil?

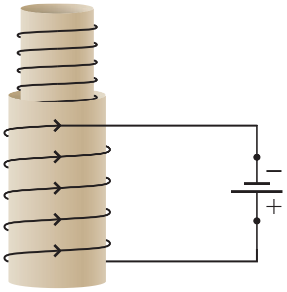

Figure 7

43. In **Figure 8,** a magnetic field increases from zero to a maximum in the direction shown. Will a current be induced in the wire and, if so, in which direction? Explain. (13.2) T/I C

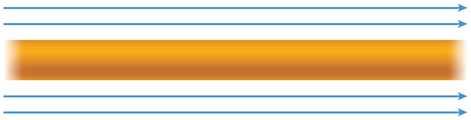

Figure 8

44. In **Figure 9**, a north pole of a magnet is moved out of the page above a conductor. Is a current induced in the wire and, if so, in which direction? Explain. (13.2) T/I C

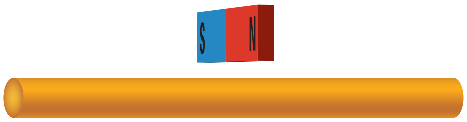

Figure 9

45. Coil type A has 25 windings per centimetre, whereas coil type B has 10 windings per centimetre. If a student has 14 cm of coil type A, how much of coil type B is needed to produce the same amount of current in a changing magnetic field for both coils? Ignore the resistances of the wires. (13.2) T/I

46. Your teacher gives you an existing coil of wire and gives you permission to uncoil it. How would you change the design of the coil to reduce the amount of induced current by a factor of two? You may ignore resistance in your thinking. (13.2) T/I

47. When a magnet is brought into a copper loop it induces a current for a short time. (13.2) T/I C A
   (a) Why does the current stop?
   (b) What would happen if the loop were made of a superconducting material? What would the resulting net magnetic field be?

48. For the coil AC generators in **Figure 10**, what is the magnetic polar orientation of the shaded region, and in which direction is the conventional current moving? (13.4) T/I

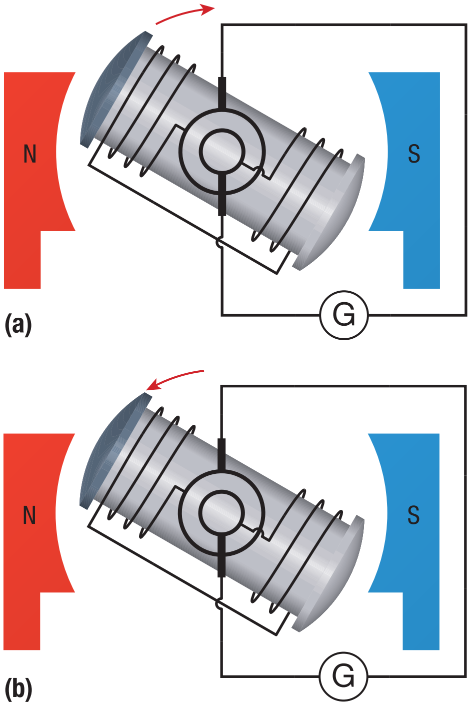

Figure 10

49. For the coil AC generator in **Figure 11**, if the current is moving in the direction indicated, what is the magnetic polar orientation of the shaded region, and in which direction is the coil spinning? (13.4) T/I

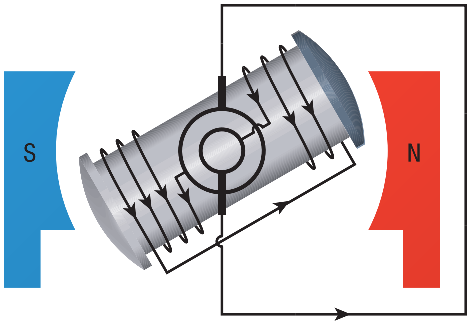

Figure 11

50. The primary circuit of a transformer has a potential difference of 200 V with 120 coils. The secondary circuit has a potential difference of 50 V. (13.5) T/I
    (a) How many coils are in the secondary circuit?
    (b) If the total resistance in the primary circuit is 10 Ω, what is the current in both circuits?
51. The primary circuit of a transformer carries 30.0 A of current and has 50 coils. The secondary circuit has 150 coils. (13.5) T/I
    (a) What is the current in the secondary circuit?
    (b) If the total resistance in the secondary circuit is 4.2 Ω, what are the potential differences of both circuits?
52. The primary circuit of a transformer has 70 coils and a total resistance of 25 Ω. The secondary circuit has 280 coils and a potential difference of 7.00×10^2 V. (13.5) T/I
    (a) What is the potential difference in the primary circuit?
    (b) What is the resistance in the secondary circuit?
53. The primary circuit of a transformer has a potential difference of 2.0 kV and a total resistance of 5.00×10^2 Ω. The secondary circuit has a potential difference of 1.00×10^2 V and 50 coils. (13.5) T/I
    (a) How many coils are in the primary circuit?
    (b) What is the resistance in the secondary circuit?
54. A power plant produces 1500 MW of power that is stepped up to a potential difference of 3.00×10^2 kV for transmission. If the total resistance in the wire is 0.150 Ω and there is no loss of power in the transformer, what is the percentage loss of power due to transmission? (13.5, 13.6) T/I
55. A wind power plant produces 12 MW of power that is stepped up to a potential difference of 1.00×10^2 kV for transmission. If there is a 0.90 % loss of power due to transmission, what is the total resistance in the transmission wire? Assume there is no power loss in the transformer. (13.5, 13.6) T/I
56. A hydroelectric dam produces power that is stepped up to a potential difference of 220 kV. There is a 0.70 % loss of power due to transmission through a wire with a total resistance of 0.40 Ω. How much power does the dam produce? Assume there is no power loss in the transformer. (13.5, 13.6) T/I
57. A power plant produces 1800 MW of power at a current of 30.0 kA. The power is then stepped up to a voltage of 240 kV. If the primary circuit used in the transformer has 100 windings, how many windings are used in the secondary circuit? Assume there is no power loss in the transformer. (13.5, 13.6) T/I
58. A power plant produces 2500 MW of power with a potential difference of 40.0 kV. A step-up transformer with 100 windings in the primary circuit and 500 windings in the secondary circuit is used to step up the potential difference for transmission. With what potential difference and current is the power transmitted? Assume there is no power loss in the transformer. (13.5, 13.6) T/I
59. A nuclear power plant produces power with a current of 24 kA. A transformer with 100 windings in the primary circuit and 800 windings in the secondary circuit is used to step up the potential difference to 240 kV. How much power does the nuclear plant produce? (13.5, 13.6) T/I
60. A power plant produces 1200 MW of power that is sent through a transmission line with a resistance of $\frac{2}{3}$ Ω. A transformer is used that has 120 windings in the primary circuit and 600 windings in the secondary circuit. If this changes the power loss to 0.20 %, what are the current and potential difference both before and after the transformer change? Assume there is no power loss in the transformer. (13.5, 13.6) T/I
61. The modified transformer in **Figure 12** has a normal primary circuit, but two secondary circuits. The same winding-to-voltage ratio holds for each segment. (13.5) T/I
    (a) State the equations comparing the primary voltage to the output voltage for each of the coil segments.
    (b) Energy must be conserved. Knowing this, derive an equation for the input power compared to the output power and use it to find an equation relating the input current and voltage to the output currents and voltages.
    (c) If $V_p = 120$ V, $I_p = 5.0$ A, $N_p = 100$, $N_1 = 5$, and $N_2 = 20$, what are the two secondary voltages V_1 and V_2?
    (d) Why is this type of transformer useful?

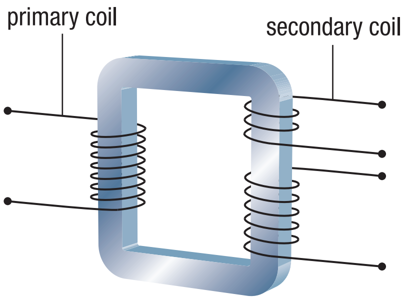

Figure 12

62. Two coils, A and B, are placed in the same magnetic field. Coil A has twice as many coils as coil B, but the material used in coil B has half the resistance of the material used to make coil A. The number of loops in a coil is directly proportional to the magnitude of the electric current induced. Knowing this, determine which coil would have more current if the magnetic field were to suddenly drop to zero. (13.1, 13.2, 13.6) T/I C

Evaluation

63. State the law of electromagnetic induction. Using Ohm's law, explain which materials should be used to induce the most current from a changing magnetic field. (13.1) T/I C
64. Using your knowledge of alternating current and electromagnetic induction, explain in your own words why you see a blue spark when you pull a plug out of an outlet too fast. Include an explanation about why it is important to turn off a device before unplugging it. (13.1, 13.2, 13.3) C A
65. Why are superconductors not used to transmit power? If superconductors were available at the time of Edison and Tesla, would Edison have won the energy battle? What would change if superconductors could be used economically in our electrical grid? (13.3, 13.6) C A

Reflect on Your Learning

66. Electromagnetic induction is probably one of the most important discoveries of all time, yet it is often taken for granted. Now that you have learned about it, how does it change the way you think about electricity? K/U C
67. Alternating current electricity can be a challenging concept for students to understand, particularly the transfer of energy. What learning happened to help you most understand alternating current? K/U C
68. A motor is essentially the opposite of a generator. Did learning about this make it easier or more difficult to understand the operation of both? Explain. K/U C
69. There are many safety devices in your home with respect to electricity. Which safety device were you most interested to learn about? Do you feel safer knowing these are in your home? Explain. K/U C A

Research

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70. Is it possible to build an electric generator that uses Earth's magnetic field? Try to estimate Earth's magnetic field strength compared to the magnetic fields used in generators. Approximately how big would the generator need to be? C A
71. The RMS voltage is a value used for equations dealing with alternating current. Research what RMS means and why the RMS voltage is used. What is the V_{RMS} value for an alternating current? Why can the "average" voltage not be used? Knowing this, what is the peak voltage for household outlets in North America? C A
72. The development of alternating current has enabled the widespread use of electricity in homes across the globe. In North America power is delivered primarily at 120 V at a frequency of 60 Hz. Research the power standards that are used in different countries, especially in Europe, in terms of voltages and frequencies used. Why are there differences? Is any standard better than another? C A
73. The electrical devices used in power plants must deal with tremendous amounts of current and power compared to what is finally delivered to our homes. Research the types of safety devices that are used in different types of power plants and how their tolerances compare to what is used for a normal household. Are typical circuit breakers and fuses used, or are completely different devices used to handle the load? C A
74. Although the principles are the same, the electric generators used in commercial power plants differ from the basic structures discussed throughout the chapter. Research a power plant and summarize how it converts resources into electricity. How are the magnetic fields and frequency of electricity generated maintained? Are there any unique design specifications that differ from the generators in the chapter? C A

Building a Model Power Plant

Power plants transform energy into electrical energy. There are three aspects to a power plant: the original source of energy; the turbine, which transforms that energy into kinetic energy; and the generator, which transforms the kinetic energy into electrical energy.

The original source of energy can come in many different forms, for example, flowing water (**Figure 1**) or wind. Whatever source is used, it provides kinetic energy to turn a turbine specifically designed for that source. For example, a turbine used to capture the energy of the wind has blades designed to turn in the wind. A turbine used to capture the energy of moving water has specific features to maximize the amount of energy captured from the water. You can see these design differences if you compare the propellers on a boat to those on an airplane.

Figure 1 This power plant converts the kinetic energy of falling water into rotational kinetic energy in a turbine and then into electrical energy.

The turbine is a critical component of a modern power plant. It is connected via a shaft to an electrical generator, which is where the kinetic energy of rotation is transformed into electrical energy using electromagnetic induction.

The Task

In this Unit Task you will model a power plant. You will need a source of energy to convert to electrical energy. Then you will need to design and build a turbine and a generator and connect them together.

An example of an energy source could be falling water, and you could model it using running water from a faucet. Alternatively, the energy source could be wind energy, and you could model it using a fan or a hair dryer (**Figure 2**).

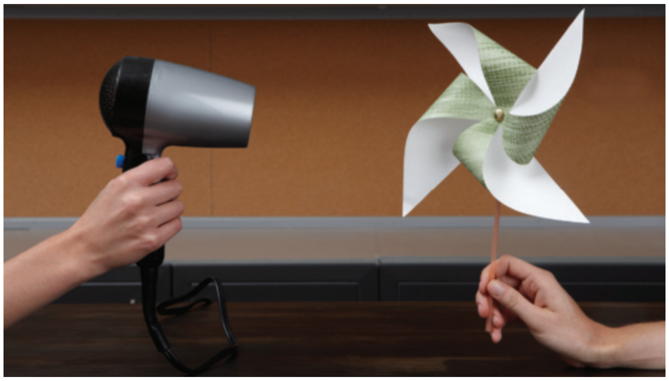

Figure 2 You could use wind power as a source of energy.

These are not the only possible ways to model a source of energy; be creative.

To make use of the source energy, you will have to transform it into rotational motion by designing and building a turbine. To generate the electricity, you will need to build a generator. When you are designing the generator, consider what factors will affect the efficiency.

Finally, to create your model power plant you will need to find a way to connect the turbine and the generator. This will require some planning. When your power plant is working, you should test the capability of your generator by measuring the electrical quantities of current and voltage.

Research and Planning

First, decide which source of energy you will use, and then design a device that will transform that energy into rotational motion. The rotation is essential to turn your generator. You may wish to research turbine designs. Note that the device you design for your source must be able to be connected to your generator. Research generator designs and decide which you will build. Look back at Section 12.6 on DC motors and Section 13.4 which explains how a generator works and how, in fact, a generator is a motor in reverse. You may want to check the motor that you built in Investigation 12.6.1; it could have components that you could use for your generator.

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Recording

Use a logbook to record the following:

- your planning notes
- all of the information you find in your research
- your testing procedures and results
- your final design

Every logbook entry should be dated and titled to indicate whether the entry is a planning note, research, testing, or the final design. The purpose of the date and title is so that you can refer to specific entries when you are making modifications. Diagrams of your design and circuit diagrams should be included. The logbook will be part of your evaluation.

Equipment and Materials

You may want to make use of some of the following equipment and materials: balsa wood, rulers, insulated wire, permanent magnets, straws, cardboard tubes, glue, adhesive tape, string. You will not necessarily use all of these and you may think of other things to use in your design.

Building the Model Power Plant

Build your generator according to your plan. You will need to measure its output using a meter, so be sure to include terminals for the connections to the meter. You will also need to connect your turbine to the generator using an axle. Be sure that the axle is long enough and appropriately constructed to connect your turbine. Build your turbine according to your plan and connect it to your generator.

Testing and Modifying

Choose appropriate electrical meters to measure the energy output of your generator. Carry out tests to determine what factors would improve your generator's energy output and determine if you are getting the most out of your source of energy and from your turbine. Calculate the efficiency of your model power plant. This will require you to determine the energy input from your source as well as the energy output of your generator. The results of your tests may lead you to reconsider your design. You may wish to review Section 13.4 on generators to help in your redesign if necessary. Modify your model according to your plan for maximizing the energy output of your power plant.

Communicating

Present your functioning model of a power plant along with your logbook to your teacher. After your presentation, be prepared to answer questions about

- how you went about designing the power plant
- how you tested the efficiency
- how you modified your design
- what variables you took into account
- what measurements you needed to take

ASSESSMENT **CHECKLIST**

Your completed Unit Task will be assessed according to the following criteria:

Knowledge/Understanding

- ✓ Research generator and turbine design.
- ✓ Demonstrate a knowledge of electromagnetic induction.
- ✓ Demonstrate a knowledge of how a generator works.
- ✓ Demonstrate a knowledge of electrical quantities and their measurement.

Thinking/Investigation

- ✓ Design a way to connect the two parts of the power plant: the turbine and the generator.
- ✓ Incorporate any necessary safety principles.
- ✓ Predict which variables will affect the efficiency of your power plant.
- ✓ Design an effective plan to test the efficiency of your power plant.
- ✓ Design an effective plan to improve the efficiency of your power plant.
- ✓ Analyze your test results.

Communication

- ✓ Use a logbook to record the details of your plan and your design in a clear and organized manner.
- ✓ Use circuit diagrams where appropriate to explain your design and testing.
- ✓ Explain your test results clearly and concisely.
- ✓ Explain why you modified your design based on test results (if you did).

Application

- ✓ Apply your knowledge of generator and turbine design to the model power plant.
- ✓ Build a generator and measure its output.
- ✓ Build the model power plant following your design.
- ✓ State which variables affected the efficiency of your power plant.
- ✓ Use an appropriate meter to measure the output of your power plant.
- ✓ Test the efficiency of your power plant.
- ✓ Modify your design based on the test results.

UNIT 5 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. Which of the following is a unit of electrical energy? (11.1) K/U
   (a) watt
   (b) volt
   (c) joule
   (d) ohm
2. Which device is used to measure the resistance of a load? (11.3, 11.5, 11.7) K/U
   (a) galvanometer
   (b) voltmeter
   (c) ohmmeter
   (d) ammeter
3. Which device is used to measure the potential difference in a circuit? (11.3, 11.5, 11.7) K/U
   (a) potential meter
   (b) ohmmeter
   (c) ammeter
   (d) voltmeter
4. Which of the following is the correct equation for Kirchhoff's voltage law for parallel loads? (11.6) K/U
   (a) $I_{\text{parallel}} = I_1 + I_2 + I_3 + \cdots$
   (b) $I_{\text{parallel}} = I_1 = I_2 = I_3 = \cdots$
   (c) $V_{\text{parallel}} = V_1 + V_2 + V_3 + \cdots$
   (d) $V_{\text{parallel}} = V_1 = V_2 = V_3 = \cdots$
5. What does the symbol in **Figure 1** represent in a circuit? (11.6) K/U
   (a) motor
   (b) battery
   (c) resistor
   (d) lamp

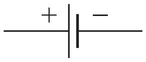


Figure 1

6. Which equation correctly describes the total equivalent resistance for a group of resistors connected in series? (11.8) K/U
   (a) $R_{\text{series}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots$
   (b) $\frac{1}{R_{\text{series}}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots$
   (c) $R_{\text{series}} = R_1 + R_2 + R_3 + \cdots$
   (d) $\frac{1}{R_{\text{series}}} = R_1 + R_2 + R_3 + \cdots$
7. Magnetic field lines
   (a) are stronger at the poles
   (b) can cross one another
   (c) are affected by gravity
   (d) exist in two dimensions only (12.1) K/U
8. Which devices use a strong magnetic field? (12.1) K/U
   (a) particle accelerators
   (b) MRI systems
   (c) Maglev trains
   (d) all of the above
9. Two parallel wires with opposing currents have which of the following effects? (12.4) K/U
   (a) They attract one another.
   (b) They repel one another.
   (c) They have no effect on one another.
   (d) They coil around one another.
10. If an external magnetic field is pointing to the right and the current in a wire is pointing out of the page, in which direction is the force on the wire? (12.5) K/U
    (a) upward
    (b) downward
    (c) left
    (d) into the page
11. Which of these allowed the technological advance from galvanometers to DC motors? (12.6) K/U
    (a) solenoids
    (b) electromagnets
    (c) split ring commutators
    (d) voltmeters
12. What will improve the strength of the magnetic field in a basic DC motor? (12.6) K/U
    (a) increasing the number of loops
    (b) adding a soft-iron core
    (c) increasing the current
    (d) all of the above
13. Which of the following devices uses a 240 V energy source? (13.3) K/U
    (a) hair dryer
    (b) television
    (c) computer
    (d) clothes dryer

14. Which of the following safety devices are commonly used throughout households and can be reset when tripped? (13.3) K/U
    (a) circuit breakers
    (b) fuses
    (c) ground fault circuit interrupters
    (d) arc fault circuit interrupters

15. At which of the following angles relative to the magnetic field will the loop in an AC generator produce the most current? (13.4) K/U
    (a) 45°
    (b) 90°
    (c) 135°
    (d) 180°

16. Which of the following transformer ratios, $\frac{N_\text{p}}{N_\text{s}}$, will produce the least voltage in the secondary circuit? (13.5) K/U
    (a) $\frac{600}{125}$
    (b) $\frac{25}{125}$
    (c) $\frac{30}{90}$
    (d) $\frac{130}{50}$

17. What equation correctly relates power, current, and resistance in a circuit? (13.6) K/U
    (a) $R = I^2P$
    (b) $P = I^2R$
    (c) $P = IR$
    (d) $P = \frac{I^2}{R}$

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

18. Electrical energy for buildings is measured in joules. (11.1) K/U

19. Voltmeters should be placed in series to measure the voltage across a load. (11.3) K/U

20. In a circuit, electrons flow in the opposite direction to the conventional current. (11.4) K/U

21. Current measures the amount of charge crossing a point for a given time interval. (11.5) K/U

22. Loads that are placed in series all have the same potential difference. (11.6) K/U

23. Placing two of the same resistors in parallel will reduce the overall resistance in a circuit. (11.8) K/U

24. Earth's magnetic field only exists outside of Earth. (12.1) K/U

25. When two unlike magnetic poles are brought close to one another, they will repel. (12.1) K/U

26. Magnetic field lines point from south to north inside a magnet. (12.1) K/U

27. Ampère found that a charge moving through a straight conductor produces a circular magnetic field around the conductor. (12.2) K/U

28. Using your left hand, if your thumb points along the direction of current in a wire, then your fingers curl in the direction of the magnetic field. (12.2) K/U

29. If the fingers of your right hand wrap around a coil in the direction of the current, then your thumb will point in the direction of magnetic north. (12.4) K/U

30. Increasing the number of loops increases the strength of a DC motor. (12.6) K/U

31. A magnetic field that changes rapidly induces more current in a conductor than a magnetic field that changes slowly. (13.1) K/U

32. Current is induced in a conductor so that the magnetic field it produces resists the change in the magnetic field that created it. (13.2) K/U

33. Most appliances in Canadian homes require a 160 V energy source. (13.3) K/U

34. A DC generator is just a DC motor that operates in reverse. (13.4) K/U

35. Step-up transformers increase the amount of current in the secondary circuit. (13.5) K/U

36. Transformers are used to step up the voltage in order to maximize power loss. (13.6) K/U

Knowledge

For each question, select the best answer from the four alternatives.

1. Which unit is given in terms of joules per second? (11.1) K/U
   (a) volts
   (b) watts
   (c) amperes
   (d) kilowatt hours
2. Coal-fired power plants convert which of the following into electrical energy? (11.1, 11.2) K/U
   (a) chemical potential energy
   (b) solar energy
   (c) nuclear potential energy
   (d) gravitational potential energy
3. Which of the following is a unit of electrical potential difference? (11.3)
   (a) joule
   (b) kilowatt
   (c) ampere
   (d) volt
4. Which device should be used to measure the current in a circuit? (11.3, 11.5, 11.7) K/U
   (a) ohmmeter
   (b) voltmeter
   (c) ammeter
   (d) circuit breaker
5. Which unit is used for electrical resistance? (11.7) K/U
   (a) volt
   (b) ohm
   (c) ampere
   (d) watt
6. Where is Earth's magnetic field the strongest? (12.1) K/U
   (a) at the equator
   (b) high above Earth
   (c) at the poles
   (d) Earth's magnetic field is uniform.
7. Which direction do magnetic field lines point inside a magnet? (12.1) K/U
   (a) from the north pole to south pole
   (b) from the south pole to the north pole
   (c) from the north pole to the centre
   (d) from the south pole to the centre
8. Which material was observed to have magnetic properties over 4000 years ago? (12.1) K/U
   (a) iron
   (b) copper
   (c) magnetite
   (d) glass
9. When using the electron flow convention to illustrate electrical current in a coil, which of the following is used to determine the direction of the resulting magnetic field? (12.2) K/U
   (a) right-hand rule for a straight conductor
   (b) left-hand rule for a coiled conductor
   (c) conventional current method
   (d) right-hand rule for a solenoid
10. Two parallel wires with current in the same direction will have which of the following effects? (12.4) K/U
   (a) The wires will attract each other.
   (b) The wires will repel each other.
   (c) The wires will curl up.
   (d) There will be no effect.
11. The motor principle states that a current-carrying conductor experiences a force
   (a) perpendicular to the magnetic field and parallel to the current
   (b) parallel to both the magnetic field and the current
   (c) perpendicular to both the magnetic field and the current
   (d) parallel to the magnetic field and perpendicular to the current (12.5) K/U
12. What will increase the amount of current induced in a coiled conductor by a changing magnetic field? (13.1) K/U
   (a) straightening the coil
   (b) adding more coils
   (c) decreasing the number of coils
   (d) changing the magnetic field more slowly
13. Which of the following transformer ratios, $\frac{N_p}{N_s}$, will produce the least voltage in the secondary circuit? (13.5) K/U
   (a) $\frac{3}{5}$
   (b) $\frac{17}{25}$
   (c) $\frac{70}{50}$
   (d) $\frac{1000}{400}$

14. In the AC generator shown in **Figure 1**, what direction is the coil turning if the current is flowing through the coil in the direction shown? (13.4) K/U

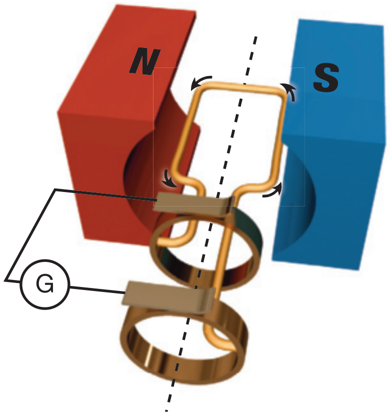


Figure 1

(a) the coil will not turn
(b) the coil turns alternately clockwise and counter-clockwise
(c) the coil will turn clockwise
(d) the coil will turn counterclockwise

15. For a given amount of power and transmission line resistance, at which voltage should a power plant transmit electricity in order to minimize the amount of power lost? (13.6) K/U
(a) 25 V
(b) 300 kV
(c) 20 kV
(d) 750 V

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

16. Electrical current is a measure of the amount of electrical potential energy associated with each charge. (11.3) K/U
17. In a circuit, electrons flow from positive to negative. (11.4, 11.5) K/U
18. Electrical current is measured in amperes. (11.5) K/U
19. Superconductors are materials that have no electrical resistance. (11.7) K/U
20. A magnetic field exists around a magnet even if it is not causing a force. (12.1) K/U
21. When two like magnetic poles are brought close to one another, they attract. (12.1) K/U
22. The right-hand rule for a straight conductor states that with your right thumb in the direction of the current in a straight wire, your fingers will curl in the direction of the magnetic field. (12.2) K/U
23. Adding a soft-iron core will decrease the strength of a DC motor. (12.6) K/U
24. Coiling a wire will increase the amount of current induced by a changing magnetic field. (13.1) K/U
25. Circuit breakers are devices that trip when too much current is drawn through a home circuit and can easily be reset. (13.3) K/U
26. A step-up transformer increases the current in the secondary circuit. (13.5) K/U
27. Power plants step up voltages when transmitting power in order to minimize energy loss. (13.6) K/U

Match each term on the left with the most appropriate description on the right.

28.	(a)	potential difference	(i)	describes how to determine the voltages and currents from loads in series and in parallel
	(b)	Ohm's law	(ii)	found that two wires with opposite currents create a repulsive force
	(c)	Kirchhoff's laws	(iii)	method used for determining the direction of a magnetic field for a current-carrying conductor
	(d)	André-Marie Ampère	(iv)	a method of electricity generation where the potential difference fluctuates
	(e)	right-hand rule for a straight conductor	(v)	measurement of the amount of energy per charge
	(f)	split ring commutator	(vi)	uses alternating current to change the potential difference in a circuit
	(g)	Lenz's law	(vii)	determines the direction of current induced by a changing magnetic field
	(h)	alternating current	(viii)	relates the potential difference to the current in a circuit
	(i)	transformer	(ix)	enabled the development of the DC motor (11, 12, 13) K/U

Understanding

Write a short answer to each question.

29. A nuclear power plant has an efficiency of 32 %. If the core nuclear reactants can provide 14 000 MW of power, how much electrical power does the power plant produce? (11.1) T/I
30. Calculate the energy needed by a 35 W light bulb that operates for 220 h. (11.1) T/I
31. Calculate the amount of power required to charge a battery if 1400 J of energy is transferred in 7.0 min. (11.1) T/I
32. The potential difference across the terminals of a light bulb is 120 V. If the bulb uses 540 J of energy, how much total charge is moved across the terminals? (11.3) T/I
33. Calculate the amount of current that flows through a wire if 0.65 C of electrons pass through a point in 1.5 min. (11.5) T/I
34. Calculate the time required for 4.0 C of charge to pass through a resistor if the current is 5.0×10^2 mA. (11.5) T/I
35. Draw a circuit with a battery and two lamps in series. (11.6) K/U
36. In the circuit shown in **Figure 2**, $I_1 = 8.5$ mA. What is I_3 if
    (a) $I_2 = 2.1$ mA?
    (b) $I_2 = I_3$? (11.6) T/I

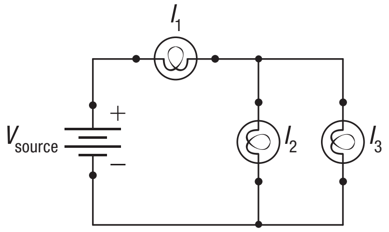


Figure 2

37. A resistor with a resistance of $9.0 \times 10^2\ \Omega$ carries 0.72 mA of current. What is the potential difference across the resistor? (11.7) T/I
38. Calculate the total resistance in the circuit shown in **Figure 3** if the resistor values are as follows: $R_1 = 7.0\ \Omega$, $R_2 = 11.4\ \Omega$, and $R_3 = 32.2\ \Omega$. (11.8) T/I

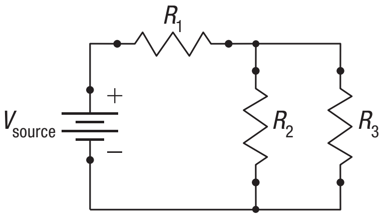


Figure 3

39. What is the difference between magnetic and gravitational fields with respect to the direction of the forces they can apply and the materials these fields act upon? (12.1) K/U
40. Draw the magnetic field lines for a bar magnet and a horseshoe magnet. Which diagram most closely resembles the magnetic field lines of Earth? (12.1) K/U C
41. Describe how iron filings have been used to understand the direction of field lines from magnets. (12.1) K/U C
42. Using the page as a frame of reference and applying the right-hand rule for a straight conductor, answer the following: (12.2) T/I
    (a) What is the direction of the current that produces a clockwise magnetic field on the page?
    (b) What is the direction of the magnetic field produced by a current directed out of the page?
    (c) For a wire carrying a current up toward the top of the page, what direction is the magnetic field on the left side of the wire?
43. Describe the experiment Oersted performed to confirm that electric currents produce magnetic fields. (12.2) K/U C
44. Draw a solenoid. Choose a direction for the current and then indicate the direction of the magnetic field this current will create. (12.4) T/I C
45. Describe conventional current in terms of electron flow. How does this affect how we determine the direction of the magnetic field produced by a wire? (12.2) K/U
46. Determine the direction of the current for the magnetic field shown in **Figure 4**. (12.2) T/I

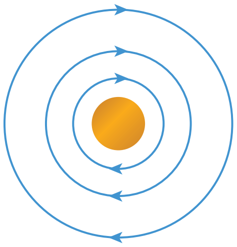


Figure 4

47. What experiment did Ampère perform and what discovery did he make? (12.4) K/U

48. Currents of unknown directions are present in two parallel wires. There is a repulsive magnetic force between the two wires. (12.4) T/I C
    (a) What do we know about the currents based on the magnetic force?
    (b) What kind of magnetic force would be produced if both of the currents in the wires were reversed?
    (c) What kind of magnetic force would be produced if only one of the currents were reversed?
    (d) What would the effect on the magnetic force be if the currents were increased in strength?
    (e) What would the effect on the magnetic force be if one of the currents was increased and the other current was switched off?

49. What is the right-hand rule for a solenoid? What other object has a similar magnetic field to that of a solenoid? (12.4) K/U

50. Explain the motor principle and how the right-hand rule applies in determining the direction of magnetic force on a current-carrying conductor. (12.5) K/U C

51. Draw and label a diagram of a simple DC motor and give a brief description of how it works. Be sure to include both moving and stationary components. (12.5, 12.6) K/U C

52. Briefly describe how a split ring commutator works and how it enables a DC motor to function. (12.6) K/U C

53. Coil A has 60 windings and coil B has 25 windings. If they are both placed in a changing magnetic field and positioned accordingly, which coil will induce more current? (13.2) K/U

54. A house has an outdoor outlet near a fenced-in pool. Given the use of water around this outlet, which safety device is most likely to be used with the outlet to prevent any electrical accidents? (13.3) K/U

55. For the single-loop AC generator in **Figure 5**, indicate in which direction the current is travelling and whether it is at a maximum, zero, or neither. (13.4) T/I C

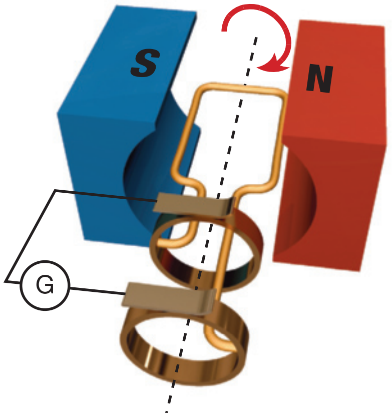


Figure 5

56. Coil A has 300 windings and coil B has 150 windings. How many more coils should be added to coil B so that it will generate the same amount of electricity as coil A in a changing magnetic field? (13.2) K/U

57. Is **Figure 6** a step-up transformer or a step-down transformer? (13.5) K/U

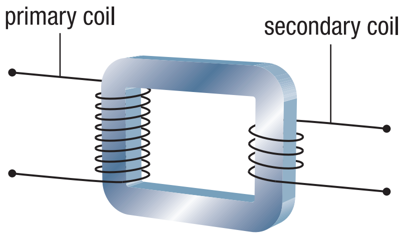


Figure 6

58. A power plant produces 1800 MW of power at a potential difference of 5.0×10^4 V. How much current is produced? (13.6) T/I

59. A solar plant produces electricity that is stepped up to a potential difference of 180 kV at a current of 35 A. If there is no energy loss in the step-up transformer, how much power does the solar plant produce? (13.6) T/I

60. A power plant produces power at a current of 3.0 kA. If the total resistance in the transmission wire is 0.40 Ω, what is the total power loss due to transmission through the wire? (13.6) T/I

61. A coal-fired power plant produces 2100 MW of power that is transmitted at a current of 5.0 kA. If there is only a 0.60 % loss of power from transmission, what is the total resistance in the transmission wire? (13.6) T/I

Analysis and Application

62. A hydroelectric power plant produces 1500 MW of power at 88 % efficiency. A nuclear power plant produces 1500 MW of power at 30 % efficiency. How much more power is wasted in the nuclear power plant than in the hydroelectric power plant? (11.1) T/I

63. A coal power plant operating at 47 % efficiency produces 3500 MW of power. When carbon capture technology is installed, the efficiency decreases to 41 %. Calculate the amount of power lost to the carbon capture technology. (11.1, 11.2) T/I

64. A battery takes 3.0×10^3 J of energy to charge. If the charger operates using 60.0 W of power but only transfers 90 % of the energy to the battery, how long will it take to charge the battery? (11.1) T/I

65. (a) Redraw the circuit in **Figure 7** to show the placement of a voltmeter to measure the value of the voltage across R_1.
    (b) Redraw the circuit in **Figure 7** to show the placement of an ammeter to measure the current through R_2. (11.3, 11.5) T/I A C

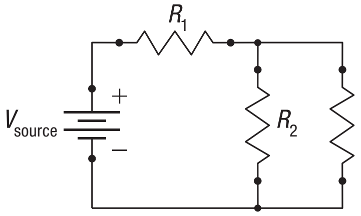


Figure 7

66. In the circuit in **Figure 8**, $V_{source} = 30.0$ V, $R_1 = 4.0 \times 10^1\ \Omega$, and $R_2 = 15\ \Omega$. After 10.0 s, how many coulombs of charge have passed through the circuit? (11.5, 11.9) T/I

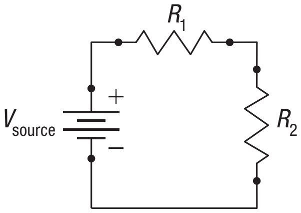


Figure 8

Refer to Figure 9 when answering Questions 67 and 68.

67. If $V_{source} = 15$ V, $R_1 = 5.0\ \Omega$, $R_2 = 20.0\ \Omega$, and $R_3 = 30.0\ \Omega$,
    (a) how many coulombs of charge have passed through the circuit after 8.0 s?
    (b) how many coulombs of charge have passed through R_2 after 10.0 s? (11.5, 11.9) T/I

68. If $V_{source} = 20.0$ V, $V_1 = 12.0$ V, $I_3 = 0.50$ A, and $R_2 = 40.0\ \Omega$,
    (a) determine R_3 and I_2
    (b) how long does it take for 15 C of charge to pass through the circuit? (11.5, 11.9) T/I

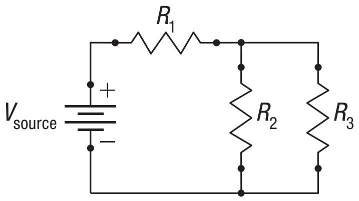


Figure 9

69. You previously learned that temperature affects electrical resistance. Incandescent light bulbs use a tiny wire filament to produce light. If you measure the resistance of an operational incandescent bulb filament, you will get a very large value. If you repeat the measurement with the light bulb off, the resistance of the filament will be very low. (11.7) T/I
    (a) Suggest a reason for the discrepancy.
    (b) Suppose now that the light bulb filament breaks. What value of resistance would you expect with the circuit on and off?

70. A student has four resistors with resistances of 6.0 Ω, 20 Ω, 30 Ω, and 18 Ω. Draw a diagram of how the student can build a circuit with a total resistance of 16.5 Ω. (11.8) T/I C

71. A student records the following values for voltage and current across a circuit (**Table 1**): (11.8) K/U T/I C

Table 1

Potential (*V*)	Current (*I*)
10 V	0.41 mA
13 V	0.51 mA
16 V	0.64 mA
19 V	0.77 mA
21 V	0.84 mA

    (a) Plot the points on a graph and draw the line of best fit.
    (b) What is the average slope of the line of best fit and what does it represent?

72. In the circuit in **Figure 10**, $R_1 = R_2$, $R_3 = 250\ \Omega$, and $R_4 = 3.0 \times 10^2\ \Omega$. If $V_{source} = 12$ V and $V_1 = 3.0$ V,
    (a) find R_1 and R_2
    (b) find I_3 (11.9) T/I

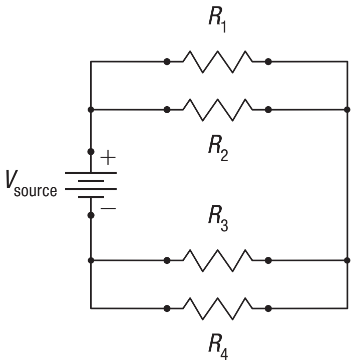


Figure 10

73. In each of the images in **Figure 11**, there is a mistake in the construction of the field lines. Copy each image and correct the mistake. (12.1) T/I A

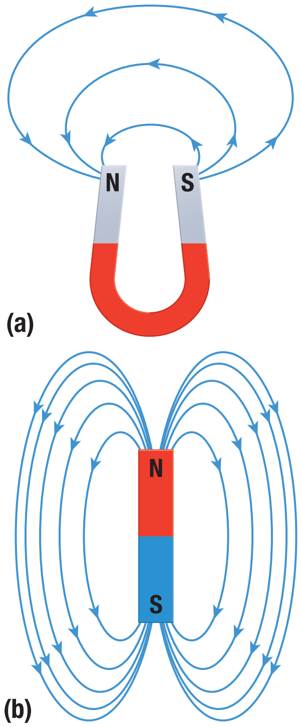


Figure 11

74. Describe how the northern lights occur and where they can be seen. Why is this effect only observed in these locations? (12.1) K/U C A

75. Describe how an electromagnet can be more useful than a permanent magnet. Include examples in your explanation. (12.4) C A

76. You are driving west in your car. Your car is equipped with a magnetic compass that displays in your rear-view mirror. You pass by a sign that says high-current cables are buried nearby and notice that your compass reads east. In which direction is current flowing in the cable? (12.4) T/I C

77. (a) Explain the right-hand rule for the motor principle.
    (b) Explain how you would orient your right hand to determine the direction of a force produced if the current moves toward the left and the external magnetic field is pointing downward.
    (c) Does the scenario you described result in a force into or out of the page? If it is neither of these, in what direction does the resultant force point? (12.5) T/I

78. Explain how a galvanometer is used in an ammeter and a voltmeter. Include a description of their circuit setups and the relative strengths of the resistors used. (12.5) K/U C A

79. Name a household object that uses a magnet. Describe how the device works. Explain whether the magnet interacts with other magnets or produces a force on a conductor, and also whether it is a permanent magnet or an electromagnet. (12.5) C A

80. With your knowledge of electricity and magnetism, explain in your own words how induction cookers and metal detectors work. (13.1) K/U C A

81. Coil type A has 20 windings per centimetre, whereas coil type B has only 15 windings per centimetre. If a student has 12 cm of coil type A, how long should he make a coil of type B in order to produce the same amount of current in a changing magnetic field for both coils? Ignore the resistances of the wires. (13.2) T/I

82. (a) Think of how DC generators are the reverse of DC motors. Is it possible to create an AC motor? Suppose that the wires of the AC generator in **Figure 12** were plugged into an AC outlet in North America. How fast would the motor spin?
    (b) Assuming the frequency of current could be changed, would this setup be practical for useful applications? If so, which ones? (12.6, 13.4) C A

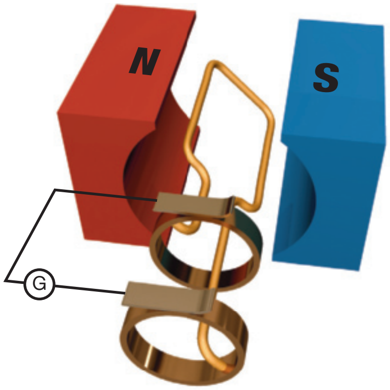


Figure 12

83. For the coil AC generator in **Figure 13**, what is the magnetic pole of the shaded region and in what direction is the current moving? (13.4) T/I

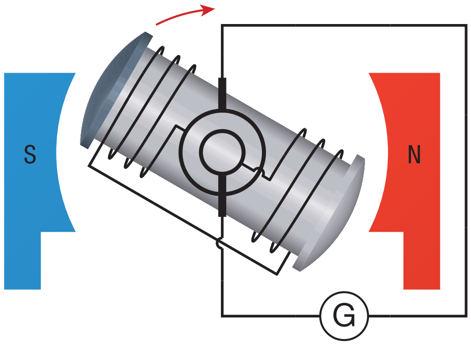


Figure 13

84. The primary circuit in a transformer delivers 5.0 A of current at 250 V. The secondary circuit delivers 10.0 A of current. (13.5) T/I
    (a) What is the voltage of the secondary circuit?
    (b) What is the ratio of the number of windings in the primary circuit to the number of windings in the secondary circuit?

85. The primary circuit in a transformer has 100 coils and a potential difference of 80.0 V. The secondary circuit has 160 coils and a current of 10.0 A. (13.5) T/I
    (a) What is the voltage of the secondary circuit?
    (b) What is the current of the primary circuit?

86. The primary circuit of a transformer has 150 coils and a potential difference of 3.0×10^2 V. The secondary circuit has a potential difference of 6.0×10^1 V. (11.7, 13.5) T/I
    (a) How many coils are in the secondary circuit?
    (b) If the total resistance in the primary circuit is 10.0 Ω, what is the current in both circuits?

87. The primary circuit of a transformer has a potential difference of 3.0 kV and a total resistance of 750 Ω. The secondary circuit has a potential difference of 1.0×10^2 V and 60 coils. (11.7, 13.5) T/I
    (a) How many coils are in the primary circuit?
    (b) What is the resistance in the secondary circuit?

88. A wind power plant produces 14 MW of power that is stepped up to a potential difference of 160 kV for transmission. If there is only a 0.80 % loss of power due to transmission, what is the total resistance in the transmission wire? Assume that there is no energy lost in the step-up transformer. (13.6) T/I

89. A hydroelectric dam produces power that is stepped up to a potential difference of 240 kV. There is a 0.60 % loss of power due to transmission through a wire with a total resistance of 0.50 Ω. How much power does the dam produce? Assume that there is no energy lost in the step-up transformer. (13.6) T/I

90. A nuclear power plant produces power with a current of 30.0 kA. A transformer with 1000 windings in the primary circuit and 6000 windings in the secondary circuit is used to step up the potential difference to 250 kV. How much power does the nuclear plant produce? Assume that there is no energy lost in the step-up transformer. (13.5, 13.6) T/I

Evaluation

91. You wish to modify a galvanometer to make it into
    (a) an ammeter
    (b) a voltmeter
    What do you need to do in each case? (11.3, 11.5, 12.5) T/I A

92. (a) Describe how a typical circuit for a household outlet is set up.
    (b) What happens to the overall resistance of the circuit as more and more objects are plugged in?
    (c) What is dangerous about this, and how are homes protected? (11.8, 11.9, 13.3) T/I C A

93. Is it possible to create a DC motor without using permanent magnets? Use your knowledge of solenoids and circuits to design a circuit that has a DC motor, power supply, wires, solenoids, and resistors. Why are resistors needed, and how can they be used to control the strength of the magnetic field? (11.8, 11.9, 12.6) K/U A

94. (a) For a magnet that passes through a loop or a coil, the current that is induced cannot attract the magnet. Explain why this must be.
    (b) Conversely, we can control the current through a coil to attract or repel a magnet as we wish. Why is this so? (12.4, 13.5) K/U

Reflect on Your Learning

95. Determine how much time you spend each week watching television or using a computer. Check your appliance's power rating and determine how much energy you use doing this each week. How much energy do you use in a year? T/I A

96. Describe in your own words how conventional current is directed and how it relates to the physical phenomena that actually happen. Does this convention matter? How were scientists able to develop electrical devices using this convention? T/I C

97. The electrical power grid is an amazing technological achievement. Prior to this unit, you probably did not give much thought to it. How would you explain how it works to members of your family? Jot down the main ideas you would talk about. K/U C

Research

GO TO NELSON SCIENCE

98. The units of measurement you learned about in this unit were named after famous scientists. Pick one of these scientists and research their lives, discoveries, and contributions to science. Write a short biography and present this to your class. T/I C

99. Compare the main energy sources used by at least three different countries across the world. T/I C A
    (a) How much energy does each country use?
    (b) Which country is best in terms of the environmental impacts of energy production?

100. Coal is one of the most abundant resources in North America, and it is estimated that even with an exponential increase in energy usage, there is enough to last for the next 200 years. Compare and contrast different types of clean coal technologies in terms of their cost to build or upgrade and the impact they can have on helping the environment. Is clean coal a feasible method of energy production for the future? T/I C A

101. Hydrogen fuel cells are an alternative to traditional batteries and gasoline in vehicles (**Figure 14**). Research this topic and write a page describing how fuel cells work, how they are recharged, and how much power they can deliver. Include information on the costs of this technology and whether or not it may be an alternative to fossil fuels. T/I C A

Figure 14

102. In the past 50 or 60 years solar cells have become a practical method for energy generation, but even so, solar power still remains at the bottom level of energy efficiency. Prepare a short report describing the development of solar cells, how they function, and why they are so inefficient. Are there any promising new innovations that could make solar technology an inexpensive alternative energy source for the future? T/I C A

103. One of Nikola Tesla's biggest dreams was to build a grid of wireless electric generators to power every home. Research this topic and explain why it was never fully developed. Using the technology and knowledge we have today, is it possible to implement these ideas? Are there devices that use this technology today? Are there any countries with plans or ideas to build a wireless power station? C A

104. The transformers discussed in Chapter 13 are only a basic example of how the technology works. The transformers used to transmit power today are much more complicated and involve multiple step ratios and circuits. Write a short article describing how this works and include a diagram showing the voltages and windings used. T/I C A

Appendices

CONTENTS

Appendix A Skills Handbook 635

A1 Safety 635
  A1.1 Safety Conventions and Symbols 635
  A1.2 Safety in the Laboratory 635

A2 Scientific Inquiry 639
  A2.1 Skills of Scientific Inquiry 639
  A2.2 Controlled Experiments 640
  A2.3 Correlational Studies 641
  A2.4 Observational Studies 642
  A2.5 Field Studies 643
  A2.6 Lab Reports 643

A3 Laboratory Skills and Techniques 645
  A3.1 Drawing and Constructing Circuits 645
  A3.2 Using the Voltmeter, Ammeter, and Digital Multimeter 646

A4 Scientific Publications 647

A5 Exploring Issues and Applications 648
  A5.1 Research Skills 648
  A5.2 Risk-Benefit Analysis Model 649

A6 Math Skills 650
  A6.1 Scientific Notation 650
  A6.2 Uncertainty in Measurements 650
  A6.3 Use of Units 652
  A6.4 Mathematical Equations 652
  A6.5 Equations and Graphs 654
  A6.6 Unit Analysis 654
  A6.7 Vectors 655

A7 Choosing Appropriate Career Pathways 659

Appendix B Reference .660

SI Base Units 660
Some SI-Derived Units 660
Numerical Prefixes 661
The Greek Alphabet 661
Physical Constants 662
Data for Some Radioisotopes 662
Periodic Table of the Elements 664

Appendix C Answers .666

SKILLS HANDBOOK **LINKS**

Throughout this textbook you will see links to the Skills Handbook, where appropriate, in each activity. These links identify supporting material in the Skills Handbook that will help you with that activity.

APPENDIX A SKILLS HANDBOOK

A1 Safety

A1.1 Safety Conventions and Symbols

Although we make every effort to make the science experience a safe one, there are some inherent risks. These risks are generally associated with the materials and equipment used, and with disregard of safety instructions when conducting investigations. Most of these risks pose no more danger than we normally experience in everyday life. We can reduce these risks by doing the following: being aware of the possible hazards, knowing the rules, behaving appropriately, and using common sense.

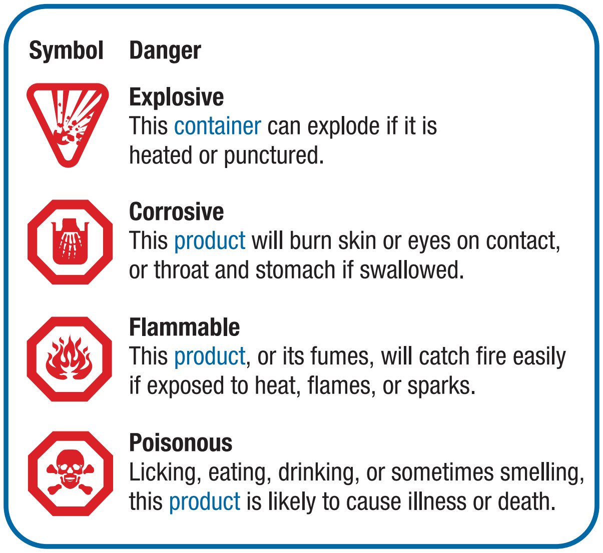
Remember, you share the responsibility not only for your own safety, but also for the safety of those around you (**Figure 1**). Always alert your teacher in case of an accident. In this textbook, chemicals, equipment, and procedures that are hazardous are indicated by the appropriate Workplace Hazardous Materials Information System (WHMIS) symbol or by ✋.

Figure 1 Taking the proper safety precautions will ensure a safe environment for you and your classmates.

WHMIS SYMBOLS AND HHPS

The Workplace Hazardous Materials Information System (WHMIS) provides workers and students with complete and accurate information about hazardous products. All chemical products supplied to schools, businesses, and industries must contain standardized labels and be accompanied by a Material Safety Data Sheet (MSDS). The MSDS provides detailed information about the product. Clear and standardized symbols are an important component of WHMIS (**Table 1**, p. 636). These symbols must be present on the product's original container and shown on other containers if the product is transferred.

The *Canadian Hazardous Products Act* requires manufacturers of consumer products containing chemicals to include a symbol that specifies the nature of the hazard and whether it is the container or the contents that is dangerous. In addition, the label must state any secondary hazards, first-aid treatment, storage, and disposal. Household Hazardous Product Symbols (HHPS) are used to show the type of hazard. The shape of the frame around the symbol indicates whether the hazard is due to the contents or the container (**Figure 2**).



Symbol	Danger
	Explosive This container can explode if it is heated or punctured.
	Corrosive This product will burn skin or eyes on contact, or throat and stomach if swallowed.
	Flammable This product, or its fumes, will catch fire easily if exposed to heat, flames, or sparks.
	Poisonous Licking, eating, drinking, or sometimes smelling, this product is likely to cause illness or death.

Figure 2 Household Hazardous Product Symbols (HHPS) appear on many products. A triangular frame indicates that the container is potentially dangerous. An octagonal frame indicates that the contents pose a hazard.

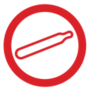
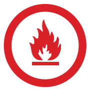
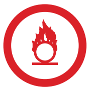
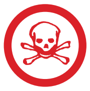
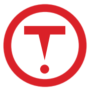
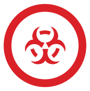
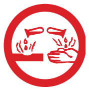
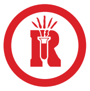
A1.2 Safety in the Laboratory

Safety in the laboratory is an attitude and a habit more than it is a set of rules. It is easier to prevent accidents than to deal with the consequences of an accident. Most of the following rules are common sense:

- Do not enter a laboratory unless a teacher or other supervisor is present, or you have permission to do so.
- Know your school's safety regulations.
- Tell your teacher about any allergies or medical problems you may have.
- Wear eye protection, a lab apron, and safety gloves when instructed by your teacher. Wear closed shoes.
- Tie back long hair and wear a protective lab coat over loose clothing. Remove any loose jewellery and finger rings.
- Keep yourself and your work area tidy and clean. Keep aisles clear.
- Never eat, drink, or chew gum in the laboratory.

(Section A1.2 continues on p. 637.)

Table 1 The Workplace Hazardous Materials Information System (WHMIS)

Class and type of compounds	WHMIS symbol	Risks	Precautions
Class A: *Compressed Gas* Material that is normally gaseous and kept in a pressurized container		• could explode due to pressure • could explode if heated or dropped • possible hazard from both the force of explosion and the release of contents	• ensure container is always secured • store in designated areas • do not drop or allow to fall
Class B: *Flammable and Combustible Materials* Materials that will continue to burn after being exposed to a flame or other ignition source		• may ignite spontaneously • may release flammable products if allowed to degrade or when exposed to water	• store in designated areas • work in well-ventilated areas • avoid heating • avoid sparks and flames • ensure that electrical sources are safe
Class C: *Oxidizing Materials* Materials that can cause other materials to burn or support combustion		• can cause skin or eye burns • increase fire and explosion hazards • may cause combustibles to explode or react violently	• store away from combustibles • wear body, hand, face, and eye protection • store in container that will not rust or oxidize
Class D: *Toxic Materials Immediate and Severe* Poisons and potentially fatal materials that cause immediate and severe harm		• may be fatal if ingested or inhaled • may be absorbed through the skin • small volumes have a toxic effect	• avoid breathing dust or vapours • avoid contact with skin or eyes • wear protective clothing, and face and eye protection • work in well-ventilated areas and wear breathing protection
Class D: *Toxic Materials Long Term Concealed* Materials that have a harmful effect after repeated exposures or over a long period		• may cause death or permanent injury • may cause birth defects or sterility • may cause cancer • may be sensitizers causing allergies	• wear appropriate personal protection • work in well-ventilated areas • store in appropriate designated areas • avoid direct contact • use hand, body, face, and eye protection • ensure respiratory and body protection is appropriate for the specific hazard
Class D: *Biohazardous Infectious Materials* Infectious agents or a biological toxin causing a serious disease or death		• may cause anaphylactic shock • includes viruses, yeasts, moulds, bacteria, and parasites that affect humans • includes fluids containing toxic products • includes cellular components	• special training is required to handle materials • work in designated biological areas with appropriate engineering controls • avoid forming aerosols • avoid breathing vapours • avoid contamination of people and/or area • store in special designated areas
Class E: *Corrosive Materials* Materials that react with metals and living tissue		• eye and skin irritation on exposure • severe burns/tissue damage on longer exposure • lung damage if inhaled • may cause blindness if contacts eyes • environmental damage from fumes	• wear body, hand, face, and eye protection • use breathing apparatus • ensure protective equipment is appropriate • work in well-ventilated areas • avoid all direct body contact • use appropriate storage containers and ensure nonventing closures
Class F: *Dangerously Reactive Materials* Materials that may have unexpected reactions		• may react with water • may be chemically unstable • may explode if exposed to shock or heat • may release toxic or flammable vapours • may vigorously polymerize • may burn unexpectedly	• handle with care avoiding vibration, shocks, and sudden temperature changes • store in appropriate containers • ensure storage containers are sealed • store and work in designated areas

Section A1.2 continued

- Know the location of MSDS information, exits, and all safety equipment, such as the first-aid kit, fire blanket, fire extinguisher, and eyewash station, and be familiar with their contents and operation.
- Avoid moving suddenly or rapidly in the laboratory, especially near chemicals or sharp instruments.
- If you are not sure what to do, ask your teacher for directions.
- Never change anything, or start an activity or investigation on your own, without your teacher's approval.
- Before you start an investigation that you have designed yourself, get your teacher's approval.
- Never attempt unauthorized experiments.
- Never work in a crowded area or alone in the laboratory.
- Always stand up when doing laboratory practical work. Do not sit down.
- Wash your hands with soap and warm water when you finish an investigation, and before you leave the laboratory.
- Use stands, clamps, and holders to secure any potentially dangerous or fragile equipment that could be tipped over.
- Do not taste any substance in a laboratory.
- Never smell chemicals unless specifically instructed to do so by your teacher. Do not inhale the vapours, or gas, directly from the container. Take a deep breath to fill your lungs with air, then waft or fan the vapours toward your nose.
- Report all accidents.
- Inform your teacher of any spills and follow your teacher's instructions on how to clean up the spill. Clean up all spills, even water spills, immediately.
- Remember safety procedures when you leave the laboratory. Accidents can also occur outdoors, at home, and at work.

EYE, EAR, AND FACE SAFETY

- Always wear approved eye protection in a laboratory. Keep the safety glasses or goggles over your eyes, not on top of your head. For certain experiments, full face protection may be necessary.
- If you must wear contact lenses in the laboratory, be extra careful; whether or not you wear contact lenses, do not touch your eyes without first washing your hands. If you do wear contact lenses, make sure that your teacher is aware of it. Carry your lens case and a pair of glasses with you.
- If you wear prescription eyeglasses, you must still wear the appropriate eye protection on top of them.
- Do not stare directly at any bright source of light (for example, a burning magnesium ribbon, laser pointers, the Sun). You will not feel any pain if your retina is being damaged by intense radiation. You cannot rely on the sensation of pain to protect you.
- If a piece of glass or other foreign object enters your eye, seek immediate medical attention.
- Always wear ear protection when experimenting with loud sounds.

HANDLING GLASSWARE SAFELY

- Never use glassware that is broken, cracked, or chipped. Give such glassware to your teacher or dispose of it as directed. Do not put the item back into circulation.
- Never pick up broken glassware with your fingers. Use a broom and dustpan.
- Dispose of glass fragments in special containers marked "Broken Glass."
- Check with your teacher before heating any glassware. Heat glassware only if it is approved for heating.
- Be very careful when cleaning glassware. There is an increased risk of breakage from dropping when the glassware is wet and slippery.
- If you cut yourself, inform your teacher immediately and get appropriate first aid.

Embedded glass or continued bleeding requires medical attention.

USING SHARP INSTRUMENTS SAFELY

- Make sure that your instruments are sharp. Dull cutting instruments require more pressure than sharp instruments and are, therefore, much more likely to slip.
- Select the appropriate instrument for the task. Never use a knife when scissors would work best.
- Always cut away from yourself and others.
- If you cut yourself, inform your teacher immediately and get appropriate first aid.

HEAT SAFETY

- Make sure that heating equipment, such as the burner, hot plate, or electric heater, is secure on the bench and clamped in place when necessary.
- Do not use a laboratory burner near wooden shelves, flammable liquids, or any other item that is combustible.
- Do not allow overheating if you are performing an experiment in a closed area. For example, if you are using a light source in a large cardboard box, be sure you have enough holes at the top of the box and on the sides to dissipate heat.
- Always assume that hot plates and electric heaters are hot and use protective gloves when handling.

- Do not touch a light source that has been on for some time. It may be hot and cause burns.
- In a laboratory where burners or hot plates are being used, never pick up a glass object without first checking the temperature by placing your hand near but not touching it. Glass and metal items that have been heated may not appear to be hot, but can cause burns.
- If you burn yourself, *immediately* run cold water gently over the burned area or immerse the burned area in cold water and inform your teacher.
- Never look down the barrel of a laboratory burner.
- Always pick up a burner by its base, never by its barrel.
- Never leave a lighted burner unattended.
- Any metal powder can be explosive. Do not put these in a flame.
- To heat a beaker, put it on the hot plate and secure with a ring support attached to a utility stand. (Placing a wire gauze under the beaker is optional.)
- Remember to include a cooling time in your experiment plan; do not put away hot equipment.

FIRE SAFETY

- Immediately inform your teacher of any fires. A very small fire in a container may be extinguished by covering the container with a wet paper towel or a ceramic square to cut off the supply of air. Alternatively, sand may be used to smother small fires. A bucket of sand with a scoop should be available in the laboratory.
- If anyone's clothes or hair catch fire, tell the person to drop to the floor and roll. Then use a fire blanket to smother the flames. Never wrap the blanket around a standing person on fire.
- For larger fires, immediately evacuate the area. Call the office or sound the fire alarm. Do not try to extinguish larger fires. As you leave the classroom, make sure that the windows and doors are closed.
- If you use a fire extinguisher, direct the extinguisher at the base of the fire and use a sweeping motion, moving the extinguisher nozzle back and forth across the front of the fire's base.

ELECTRICAL SAFETY

- Do not operate electrical equipment near running water or a large container of water. Water or wet hands should never be near electrical equipment such as a hot plate, a light source, or a microscope.
- Check the condition of electrical equipment. Do not use it if wires or plugs are damaged, or if the ground pin has been removed.
- If using a light source, check that the wires of the light fixture are not frayed, and that the bulb socket is in good shape and well secured to a stand.
- Make sure that electrical cords are not placed where someone could trip over them.
- When unplugging equipment, remove the plug gently from the socket. Do not pull on the cord.
- When using variable power supplies, start at low voltage and increase slowly.

WASTE DISPOSAL

Waste disposal at school, at home, and at work is a societal issue. Most laboratory waste can be washed down the drain or, if it is in solid form, placed in ordinary garbage containers. However, some waste must be treated more carefully. It is your responsibility to follow procedures and to dispose of waste in the safest possible manner according to your teacher's instructions.

FIRST AID

The following guidelines apply in case of an injury, such as a burn, cut, chemical spill, ingestion, inhalation, or splash in the eyes:

- Always inform your teacher immediately of any injury.
- If the injury is a minor cut or abrasion, wash the area thoroughly. Using a compress (for example, clean paper towels), apply pressure to the cut to stop the bleeding. When bleeding has stopped, replace the compress with a sterile bandage. If the cut is serious, apply pressure and seek medical attention immediately.
- If you get a solution in your eye, quickly use the eyewash or nearest running water. Continue to rinse the eye with water for at least 15 min. Unless you have a plumbed eyewash system, you will also need assistance in refilling the eyewash container. Have another student inform your teacher of the accident. The injured eye should be examined by a doctor.
- If the injury is a burn, immediately immerse the affected area in cold water, or run cold water gently over the burned area. This will reduce the temperature and prevent further tissue damage.
- In case of electric shock, unplug the appliance and do not touch it or the victim. Inform your teacher immediately.
- If a classmate's injury has rendered him/her unconscious, notify your teacher immediately. Your teacher will perform CPR if necessary. Do not administer CPR unless under specific instructions from your teacher. Call the school office and request emergency medical help.

A2 Scientific Inquiry

In our attempts to further our understanding of the natural world, we encounter questions, mysteries, or events that are not readily explainable. To develop explanations, we investigate using scientific inquiry. An important aspect of scientific inquiry is that science is only one of many ways people explore, explain, and come to know the world around them. Scientific inquiry is a multifaceted process that involves the following: identifying questions that can be answered through scientific investigations; using appropriate tools and techniques to gather, analyze, and interpret data; developing descriptions, explanations, predictions, and models using evidence; thinking critically and logically to make the relationships between evidence and explanations; recognizing and analyzing alternative explanations and predictions; and communicating scientific procedures and explanations.

The methods used in scientific inquiry depend, to a large degree, on the purpose of the inquiry. There are four common types of scientific inquiry: (1) the controlled experiment, (2) the correlational study, (3) the observational study, and (4) the field study. These types of scientific inquiry require specific skills. The skills are discussed below, followed by a detailed description of how they relate to each of the four types of scientific inquiry.

A2.1 Skills of Scientific Inquiry

Scientific inquiry requires certain skills that are important in the process of conducting an investigation. These skills can be organized into four categories: initiating and planning, performing and recording, analyzing and interpreting, and communicating.

INITIATING AND PLANNING

(1) Questioning: Most scientific investigations begin with a question. It is important to ask the right questions. In certain types of scientific inquiry, the question must be testable. This means that it must ask about a possible cause-and-effect relationship. A cause-and-effect relationship is one in which a change in one variable (see #3) causes a change in another variable. A testable question might start in one of the following ways: What causes . . . ? How does . . . affect . . . ? If . . . , what happens to . . . ?

(2) Researching: This is a skill that occurs across all four categories of scientific inquiry and includes preparing for research, accessing resources, processing information, and transferring learning. The process involves identifying the type of information that is required, using strategies to locate and access the information, recording the information, synthesizing findings, and formulating conclusions.

(3) Identifying variables: Considering the variables involved in an investigation is an important step in designing an effective investigation. Variables are any factors that could affect the outcome of an investigation. There are three kinds of variables in a controlled experiment: the manipulated variable, the responding variable, and the controlled variables.

- The manipulated variable (also known as the independent variable or cause variable) is the variable that is deliberately changed by the investigator.
- The responding variable (also known as the dependent variable or effect variable) is the variable that the investigator believes will be affected by a change in the manipulated variable.
- The controlled variables are variables that may affect the responding variable, but that are held constant so that they cannot affect the responding variable. A controlled experiment is a test of whether (and how) a manipulated variable affects a responding variable. To make the test fair, all other variables that may affect the responding variable are kept constant (unchanging).

(4) Hypothesizing: A hypothesis is a predicted answer to the testable question. It proposes a possible explanation based on an already known scientific theory, law, or other generalization.

A hypothesis may be written in the form of an "If . . . , then . . . because . . ." statement. If the manipulated (independent) variable is changed in a particular way, then we predict that the responding (dependent) variable will change in a particular way, and we provide a theoretical explanation for the prediction. You may create more than one hypothesis from the same testable question. For example,

If an air-filled balloon is placed in a freezer and its temperature is decreased, then its volume will decrease because, according to the kinetic molecular theory, atoms and molecules slow down and occupy less space at lower temperatures.

When you conduct an investigation, your observations do not always support the prediction in your hypothesis. When this happens, you may re-evaluate and modify your hypothesis and design a new experiment.

(5) Planning: Planning an inquiry activity involves developing an experimental design, identifying variables, selecting necessary equipment and materials, addressing safety concerns, and writing a step-by-step procedure.

PERFORMING AND RECORDING

(1) Conducting inquiry: As you perform an investigation, follow the steps in the procedure carefully and thoroughly. Check with your teacher if you find that you need to make significant alterations to your

procedure. Use all equipment and materials safely, appropriately, and with precision.

(2) Making observations: When you conduct an investigation, you should make accurate observations at regular intervals and record them carefully and accurately. Record exactly what you observe. Observations from an experiment may not always be what you expect them to be. Qualitative (descriptive) and quantitative (measured) observations may be made during an investigation. Some observations may also be provided for you during an investigation.

Quantitative observations are based on measured quantities, such as temperature, volume, and mass. They are usually recorded in data tables.

Qualitative observations describe characteristics that cannot be expressed in numbers, such as texture, smell, and taste. They can be recorded using words, pictures, tables, or labelled diagrams.

(3) Collecting, organizing, and recording data: During an investigation you should collect and record all data and observations, and organize these into formats that are easily interpreted (such as tables, charts, etc.).

ANALYZING AND INTERPRETING

(1) Analyzing: Analyzing involves looking for patterns and relationships that will help you explain your results and give you new information about the question you are investigating. Your analysis will tell you whether your observations support your hypothesis.

(2) Evaluating: It is very important to evaluate the evidence that is obtained through observations and analysis. When evaluating the results of an investigation here are some aspects you should consider:

- Experimental design: Were there any problems with the way you planned your experiment? Did you control all the variables except for the manipulated variable?
- Equipment and materials: Was the equipment adequate? Would other equipment have been better? Was something used incorrectly? Did you have difficulty with a piece of equipment?
- Skills: Did you have the appropriate skills for the investigation? Did you have to use a skill that you were just beginning to learn?
- Observations: Did you accurately record all the relevant observations?

COMMUNICATING

(1) It is important to share both your process and your results. Other people may want to repeat your investigation, or they may want to use or apply your results in another situation. Your write-up or report should reflect the process of scientific inquiry that you used in your investigation.

(2) At this stage, you should be prepared to extend insights and opinions from your findings, suggest areas for further investigation, and relate research findings to the world around you.

In the following sections, we will detail the components of the four types of investigation: controlled experiments, correlational studies, observational studies, and field studies.

A2.2 Controlled Experiments

A controlled experiment is an example of scientific inquiry in which a manipulated variable is intentionally changed to determine its effect on a responding variable. All other variables are controlled (kept constant). Controlled experiments are performed when the purpose of the inquiry is to create, test, or use a scientific concept.

The common components of controlled experiments are outlined below. Note that there are normally many cycles through the steps during an actual experiment.

TESTABLE QUESTION

A testable question forms the basis for your controlled experiment: the investigation is designed to answer the question. Controlled experiments are about relationships among variables, so your question could be about the effects on variable A when variable B is changed.

VARIABLES

The primary purpose of a controlled experiment is to determine whether a change in a manipulated variable causes a noticeable change in a responding variable while all other variables remain constant. Therefore, you must identify all major variables that you will measure and/or control in your investigation. What is the manipulated (independent) variable? What is the responding (dependent) variable? What are the controlled variables?

When conducting a controlled experiment, change only one manipulated variable at a time, holding all the others (except the responding variable) constant. This way, you can assume that the results are caused by the manipulated variable and not by any of the other variables.

HYPOTHESIS

When formulating a hypothesis, first read the testable question, the experimental design, and the procedure, if provided. Then, try to identify (and distinguish) the manipulated variable, the responding variable, and the controlled variables. Your hypothesis will be a predicted answer to the testable question accompanied by a theoretical explanation for your prediction.

EXPERIMENTAL DESIGN

The design of a controlled experiment shows how you plan to answer your question. The design outlines how you will change the manipulated variable, measure any variations in the responding variable, and control all the other variables. It is a summary of your plan for the experiment.

EQUIPMENT AND MATERIALS

Make a detailed list of all equipment and materials used, including sizes and quantities where appropriate. Be sure to include safety equipment, such as eye protection, lab apron, protective gloves, and tongs, where needed. Draw a diagram to show any complicated setup of apparatus.

PROCEDURE

Write a step-by-step description of how you will perform your investigation. It must be clear enough for someone else to follow and it must explain how you will deal with each of the variables in your investigation. The first step in a procedure usually refers to any safety precautions that need to be addressed, and the last step relates to any cleanup that needs to be done.

OBSERVATIONS

There are many ways you can gather and record observations during your investigation. It is helpful to plan ahead and think about what data you will need to answer the question and how best to record them (for example, data tables, pictures, or labelled diagrams may be helpful). This helps to clarify your thinking about the question posed at the beginning, the variables, the number of trials, the procedure, the materials, and your skills. It will also help you organize your evidence for easier analysis.

ANALYZE AND EVALUATE

You will need to analyze and interpret your observations—this may include graphing your data and analyzing any patterns or trends that may be evident in your graphs. After thoroughly analyzing your observations, you may have sufficient and appropriate evidence to enable you to answer the testable question posed at the beginning of the investigation.

You must evaluate the processes that you followed to plan and perform the investigation. You will also evaluate the outcome of the investigation, which involves evaluating your hypothesis/prediction. You must identify and take into account any sources of error and uncertainty in your measurements.

Finally, compare your hypothesis/prediction with the evidence. Is your hypothesis supported by the evidence?

APPLY AND EXTEND

Reflect on how your investigation relates to the world around you: how can you use what you have learned in everyday life?

REPORTING ON THE INVESTIGATION

Your lab report should describe your planning process and procedure clearly and in enough detail that the reader could repeat the experiment exactly as you performed it. You should present your observations, your analysis, and your evaluation of your experiment clearly, accurately, and honestly.

A2.3 Correlational Studies

When the purpose of scientific inquiry is to test a suspected relationship between two different variables, but a controlled experiment is not possible, a correlational study is conducted. In a correlational study, the investigator tries to determine whether one variable is affecting another without purposely changing or controlling any of the variables. Instead, variables are allowed to change naturally. It is often difficult to isolate cause and effect in correlational studies. A correlational inquiry requires very large sample numbers and many replications to increase the certainty of the results.

A correlational study does not require experiments or fieldwork; for example, the investigator can use databases prepared by other researchers to find relationships between two or more variables. The investigator can, however, choose to also make observations and measurements through fieldwork, interviews, and surveys.

A hypothesis or prediction is not useful in a correlational study. Correlational studies are not intended to establish cause-and-effect relationships. However, the results of a correlational study can be used to formulate a hypothesis about the causal relationship between the variables.

The common components of a correlational study are outlined below. Even though the sequence is presented as linear, there are normally many cycles through the steps during an actual study.

PURPOSE

When planning a correlational study, it is important that you pose a question about a possible statistical relationship between variable A and variable B. Choose a topic that interests you. Determine whether you are going to replicate or revise a previous study, or create a new one. Indicate your decision in the statement of the purpose.

VARIABLES

In a correlational study you must determine whether two variables are related, without controlling any of the variables. You must identify all the major variables that will be measured and/or observed in your investigation.

STUDY DESIGN

When designing your correlational study you must identify the setting and the methods you will use in carrying out your investigation. You should describe the type(s) of data you plan to collect and its sources. Your design should address questions such as the following: Will you be conducting a survey? If so, where will the survey be conducted? Who will answer your questionnaire? When will the survey be conducted? How often will the survey be administered? If you are obtaining information from an existing database, then describe the source of the information and your plans for analyzing the information.

EQUIPMENT AND MATERIALS

Make a detailed list of all equipment and materials used, including sizes and quantities where appropriate. Be sure to include safety equipment, such as eye protection and ear protection, where needed. Draw a diagram to show any complicated setup of apparatus.

PROCEDURE

Write a step-by-step description identifying how you will gather data on the variables under study. You will also need to identify potential sources of data. There are two possible sources: observations made by you, the investigator; and existing data (databases, etc.).

OBSERVATIONS

If you are collecting your own data through observation then you will need to plan ahead and think about what data you will need and how best to record them. There are many ways to gather and record your observations (such as data tables, pictures, or labelled diagrams). This is an important step because it helps to clarify your thinking about the question posed at the beginning, the variables, the procedure, the materials, and your skills. It will also help you organize your observations for easier analysis.

ANALYZE AND EVALUATE

You will need to analyze and interpret your observations or sourced data—this will usually include graphing the data and analyzing any patterns or trends that may be evident in your graphs. You will need to identify the relationship between your two variables. A positive correlation indicates a direct relationship between variables: an increase in one variable corresponds to an increase in another. A negative correlation indicates an inverse relationship: an increase in one variable corresponds to a decrease in the other variable. If there is no relationship between the variables then there is no correlation.

After thoroughly analyzing your observations, you may have sufficient and appropriate evidence to enable you to answer the question you posed at the beginning of the investigation. Was there a relationship between variable A and variable B?

Evaluate the processes that you followed to plan and perform the investigation. Also evaluate the outcome of the investigation, which involves evaluating any prediction you made at the beginning of the investigation. You must identify and take into account any sources of error and uncertainty in your measurements.

APPLY AND EXTEND

Reflect on how your investigation relates to the world around you: how can you use what you have learned in your everyday life?

REPORTING ON THE INVESTIGATION

In preparing your report, your objectives should be to describe your design and procedure accurately and to report your observations, analyses, and evaluations accurately and honestly.

A2.4 Observational Studies

Often, the purpose of an inquiry is simply to study a natural phenomenon with the intention of gaining scientifically significant information to answer a question. Observational studies involve observing a subject or phenomenon in an unobtrusive or unstructured manner, usually with no specific hypothesis. The inquiry does not start off with a hypothesis, but a hypothesis may be generated as information is collected.

The stages and processes of scientific inquiry through observational studies are summarized below. Even though the sequence is presented as linear, there are normally many cycles through the steps during an actual study.

PURPOSE

In planning an observational study, it is important to pose a general question about the natural world. Choose a topic that interests you. Determine whether you are going to replicate or revise a previous study, or create a new one. Indicate your decision in a statement of the purpose.

EQUIPMENT AND MATERIALS

Make a detailed list of all equipment and materials used, including sizes and quantities where appropriate. Be sure to include safety equipment, such as eye protection, lab apron, protective gloves, and tongs, where needed. Draw a diagram to show any complicated setup of apparatus.

PROCEDURE

Write a step-by-step description of how you will make your observations. It must be clear enough for someone else to follow. The first step in a procedure usually refers to any safety precautions that need to be addressed, and the last step relates to any cleanup that needs to be done.

OBSERVATIONS

There are many ways you can gather and record observations—including quantitative observations—during an observational study. All observations should be objective and unambiguous. Consider ways to organize your information for easier analysis.

ANALYZE AND EVALUATE

After thoroughly analyzing your observations, you may have sufficient and appropriate evidence to enable you to answer the question posed at the beginning of the investigation. You may also have enough observations and information to form a hypothesis for a controlled experiment.

At this stage of the investigation, you will evaluate the processes used to plan and perform the investigation. Evaluating the processes includes evaluating the materials, the design, the procedure, and your skills. The results of most such investigations will suggest further studies, perhaps controlled experiments or correlational studies, to explore tentative hypotheses you may have developed.

APPLY AND EXTEND

At this stage you should reflect on how your investigation relates to the world around you: how can you use what you have learned in your everyday life?

REPORTING ON THE INVESTIGATION

In your report, describe your design and procedure accurately, and report your observations accurately and honestly.

A2.5 Field Studies

A field study is a special case of observational study. The investigation is being conducted outside of the classroom setting and will require special planning and considerations. In most cases, there will be special safety considerations to take into account since the study is conducted in a natural environment. If a field study is conducted near a pond, lake, or stream, then water safety needs to be taken into consideration. Since field studies often involve studying living organisms in their natural environment, it is important to consider how the study will affect the biotic and abiotic components of the environment. The investigator should take steps to minimize any potentially negative effects on the organisms being studied or their environment.

A2.6 Lab Reports

When carrying out investigations, it is important that scientists keep records of their plans and results, and share their findings. In order to have their investigations repeated (replicated) and accepted by the scientific community, scientists generally share their work by publishing reports in which details of their design, materials, procedure, evidence, analysis, and evaluation are provided.

Lab reports are prepared after an investigation is completed. To ensure that you can accurately describe the investigation, keep thorough and accurate records of your activities as you carry out the investigation. Your lab book or report should reflect the type of scientific inquiry that you used in the investigation (controlled experiment, correlational study, observational study, or field study) and should be based on the following headings, *as appropriate*:

TITLE

At the beginning of your report, write the number and title of your investigation. In this book, the title is usually given, but if you are designing your own investigation, create a title that suggests what the investigation is about. Include the date the investigation was conducted and the names of all lab partners (if you worked as a team).

PURPOSE

State the purpose of the investigation. Why are you doing this investigation?

TESTABLE QUESTION

State the question that you attempted to answer in the investigation. Sometimes the question is provided for you; other times you are expected to formulate your own. If it is appropriate to do so, state the question in terms of manipulated and responding variables.

HYPOTHESIS/PREDICTION

For a controlled experiment you will usually have to compose a hypothesis or prediction. This will be a proposed answer to your testable question. When writing a hypothesis include both a prediction and a reason for the prediction, based on scientific theory, law, or other generalization. You may use the "If . . . , then . . . because . . ." form. A simple prediction may be written in the "If . . . , then . . ." form.

VARIABLES

Identify all major variables that you measured and/or controlled in the investigation. What is the manipulated variable? What is the responding variable? What are the major controlled variables?

EXPERIMENTAL DESIGN

Provide a brief general overview (one to three sentences) of what you did in your investigation. If your investigation involved manipulated, responding, and controlled variables, list them and indicate how they were changed, measured, or held constant. Identify any control or control group that was used in the investigation.

EQUIPMENT AND MATERIALS

Include a detailed list of all equipment and materials used, including sizes and quantities where appropriate. Be sure to include safety equipment, such as eye protection, lab apron, protective gloves, and tongs, where needed. Draw a diagram to show any complicated setup of apparatus.

PROCEDURE

Describe, in detailed, numbered steps, the procedure you followed to carry out your investigation. Your teacher may specify which style you should use. Examples of three common writing styles are

1. third person past tense ("The test tubes were heated . . .")
2. first person plural past tense ("We heated the test tubes . . .")
3. second person imperative ("Heat the test tubes . . .")

Include steps to clean up and dispose of waste.

OBSERVATIONS

Present your observations in a form that is easily understood. This includes all the qualitative and quantitative observations that you made. Be as precise as possible when describing quantitative observations. Include any unexpected observations and present your information clearly. If you have only a few observations, this could be a list; for controlled experiments and for many observations, a data table, labelled diagram, or written descriptions would be more appropriate.

ANALYSIS

Complete the questions found in the Analyze and Evaluate section of the investigation. These questions will prompt you to analyze and interpret your observations, answer a testable question, draw conclusions, and evaluate both your experiment and your conclusions. You will also be prompted to graph your data and analyze these graphs where applicable.

If you are writing up an investigation for which there are no questions, write your own analysis. Interpret your observations and present the evidence in the form of titled tables, graphs, or illustrations, as appropriate. Include any calculations, the results of which can be shown in a table. Make statements about any patterns or trends you observed. Conclude the analysis with a statement based only on the evidence you have gathered, answering the question that initiated the investigation.

EVALUATION

The evaluation is your judgment about the quality of evidence obtained and about the validity of the prediction and hypothesis (if present). This section can be divided into two parts:

(1) Evaluation of the experiment: Did your experiment provide reliable and valid evidence to enable you to answer the question? Consider the experimental design, the procedure, and your laboratory skills. Were they all adequate? Are you confident enough in the evidence to use it to evaluate any prediction and/or hypothesis you made?

(2) Evaluation of the prediction: Was the prediction you made before the investigation supported or falsified by the evidence? Based on your evaluation of the evidence and prediction, is the hypothesis you used to make your prediction supported, or should it be rejected?

APPLY AND EXTEND

Answer any Apply and Extend questions in the investigation. Number your answers as they appear in the Apply and Extend section in the textbook.

A3 Laboratory Skills and Techniques

A3.1 Drawing and Constructing Circuits

SOURCES OF ELECTRICAL ENERGY

To provide the electrical energy in most of the circuits you create, you will be using a combination of dry cells or a power supply. The source in the circuits you construct and test will be a direct current (DC) source of electrical energy. In a DC circuit, the current flows in only one direction.

Wall outlets provide a different kind of electrical energy known as an alternating current (AC) source. In an AC circuit, the electric current reverses its direction 60 times a second.

DRAWING CIRCUIT DIAGRAMS

There are some conventions to follow when drawing a circuit diagram (**Figure 1**): connecting wires are generally shown as straight lines or lines with 90° angles, and symbols are used to represent all the components (**Table 1**).

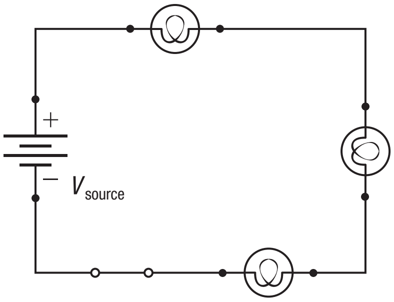
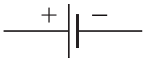
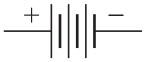
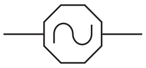
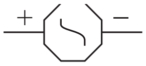
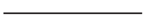
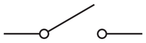
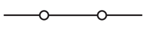
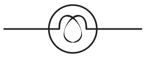
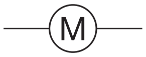
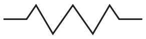
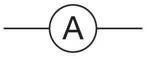
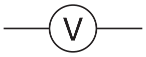
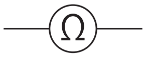


Figure 1 A circuit diagram showing an electric cell, three lamps, and a closed switch connected in series

Table 1 Circuit Diagram Symbols

	Part of circuit	Symbol
sources of electrical energy	electric cell	
	three-cell battery	
	AC power supply	
	variable DC power supply	
electrical conductor	connecting wire	
control device	switch (open)	
	switch (closed)	
loads	lamp	
	electric motor	
	resistor	
meters	ammeter	
	voltmeter	
	ohmmeter	

SAFETY CONSIDERATIONS

It is important to follow safety procedures.

- Always ensure that your hands are dry and that you are standing on a dry surface.
- Do not use faulty dry cells or batteries. Avoid connecting partially discharged dry cells to fully charged cells.
- Do not use frayed or damaged connectors.
- Only operate a circuit after it has been approved by your teacher.

CONSTRUCTING A CIRCUIT

When working with circuits, always follow the instructions. If you are unsure of the instructions, ask for help.

- Check the connections carefully when connecting dry cells in series or in parallel. Incorrect connections could cause short circuits and/or sparks.
- When attaching connecting wires to a meter, it may be helpful to colour-code the positive and negative connections. For example, connect a red wire to the positive terminal and a black wire to the negative terminal of the meter.
- Sometimes the ends of connecting wires do not have the correct attachments to connect to a device or meter. Use approved connectors, such as alligator clips, but be careful to position the connectors so that they cannot touch one another.
- Open the switch before altering a meter connection or adding new wiring or components.
- If a circuit does not operate correctly, open the switch and check the wiring and all the connections to the terminals. If you cannot find the problem, ask your teacher to inspect the circuit again.

A3.2 Using the Voltmeter, Ammeter, and Digital Multimeter

We rely on instruments that can detect and measure electricity. Two common instruments are the voltmeter and the ammeter. These instruments may be digital (providing a digital readout) or analog (indicating voltage or current by the movement of a needle across a scale). You may also use a digital multimeter, which can measure voltage, current, and resistance.

THE VOLTMETER

A voltmeter measures the electric potential difference, or voltage, between two different points in a circuit. A voltmeter can be connected across the terminals of a cell to measure the voltage of the cell, or across another component of a circuit to measure the voltage across the component. A voltmeter is always connected in parallel with the component you want to investigate.

THE AMMETER

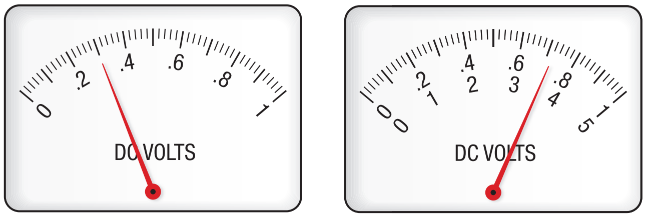
An ammeter measures the amount of electric current in a circuit. To measure the electric current, connect the ammeter directly into the circuit. Disconnect a wire from the part of the circuit you wish to measure and connect the ammeter, in series, to complete the circuit. The unit of current is the ampere (A).

THE DIGITAL MULTIMETER

A digital multimeter can measure the voltage, current, or resistance in a circuit. Using the selector knob, select the electrical quantity that you wish to measure. Then connect the wire leads properly to the appropriate place in the circuit. Remember to connect the meter in parallel for measuring voltage or resistance, or in series for measuring current. To measure resistance, the circuit must be off. The multimeter will provide a digital readout of the measurement of the electrical quantity.

READING ANALOG AND DIGITAL METERS

An analog meter has a needle that usually moves from zero at the left to a maximum value at the right. If there is only one scale, it is relatively easy to read the value, as in the meter reading in **Figure 2(a)**. If the meter has two or more scales as selected by a switch or terminal, then the value must be read on the scale that corresponds to the switch or terminal chosen. In **Figure 2(b)**, if the switch is on the 1 A setting, the reading is 0.72 A, but if the switch is on the 5 A setting, the reading is 3.6 A.



(a) **(b)**

Figure 2 An analog voltmeter showing (a) one scale and (b) two scales

A digital meter often has several options, so the reading corresponds to the option selected by the switch. For example, the digital multimeter shown in **Figure 3** is set on 2 V, which means that the maximum expected voltage is 2 V. To measure voltage, a wire (typically black) is connected to the common terminal (COM), which corresponds to the negative terminal; another wire (typically red) is connected to the voltage-resistance (V/Ω) terminal, corresponding to the positive terminal.

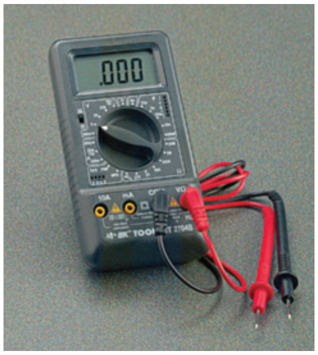


Figure 3 A digital multimeter

A4 Scientific Publications

Communicating in Science

Advances in science and our understanding of the natural world are the result of scientists sharing ideas and information. Watson and Crick won the Nobel Prize for discovering the double helix structure of DNA, but they solved this structure with the help of X-ray photographs taken by Rosalind Franklin during her own research.

It is important for scientists to share ideas and research with other scientists. New research findings are shared at conferences or in journal publications. Research scientists take pride in being published. Being published confirms that the research adds to the knowledge base of the scientific community. Sharing information helps to spread knowledge, solve problems, and inspire other scientists.

The Scientific Journal

Scientific journals are publications that are used to present new research. There are thousands of different science journals published worldwide, and in many languages. A scientific journal may be specific to a subject (for example, *Canadian Journal of Diabetes*) or contain articles that cover a variety of subjects within a field (for example, *Nature*). These publications may be electronic (online) or in print and may be published weekly, monthly, bimonthly, or quarterly.

Peer Review

When an article is submitted to a journal the research findings are critically reviewed by experts in the topic. This ensures that the research presents ideas that are supported by practices of good science. High-quality evidence and appropriate conclusions are necessary for the article to be accepted for publication. An article that is submitted to a reputable journal may take months to be approved for publication. The article may be returned to the author(s) for revision if necessary.

Scientists aim to be published in the most respected journals. The peer-review process contributes to the reputation of a journal. It helps to maintain standards and provide credibility. A scientific journal becomes reputable by ensuring that only articles of high quality are published. Very prestigious journals (such as *Nature, Science*, and *New England Journal of Medicine*) are known for publishing research backed by only the best practices of science. Reputable journals are widely read and considered reliable by the scientific community. Publication in a reputable journal brings immediate recognition for the author(s). Research that is not published in a peer-reviewed journal is often overlooked.

Format of Research Articles

Research articles have specific sections. Articles often include an abstract, introduction, methods, results, discussion, conclusions, and references.

THE ABSTRACT

The abstract is a short summary of the article. It presents the purpose of the research, outlines the design of the experiment and methods used, and summarizes findings or conclusions. A well-written abstract is useful when looking for articles with specific information. Time may be saved by reading the abstract and then deciding if the article is going to be helpful in supporting research.

CITING SOURCES AND GIVING CREDIT

Once a scientist has found useful sources and included them in an article or paper, information must be provided about the article so that someone else who is interested in learning more will be able to find it. This also shows the reader that information supporting the research is current.

More importantly, citing another scientist's work provides a measure of value of what he or she has published. It gives credit to the scientist. More citations often mean that the work is worthwhile and influential. An example of this is the frequency of citation of Kary Mullis's work that presented the polymerase chain reaction (PCR). Thousands of citations occurred within a few years of publication, confirming that his work was influential.

Further Reading

Day, R.A., & Gastel, B. (2006). *How to write and publish a scientific paper* (6th ed.). Cambridge: Cambridge University Press.

A5 Exploring Issues and Applications

Throughout this textbook you will have many opportunities to examine the connections between science, technology, society, and the environment (STSE) by exploring issues and applications.

An issue is a situation in which several points of view need to be considered in order to make a decision. There can be many positions, generally determined by the values that an individual or a society holds, on a single issue. Which solution is "best" is a matter of opinion; ideally, the solution that is implemented is the one that is most appropriate for society as a whole. Researching information about an issue will help you make an educated decision about it. All the skills listed in Section A5.1 may be useful in an activity that involves exploring an issue.

Scientific research produces knowledge or understanding of natural phenomena. Technologists and engineers look for ways to apply this knowledge in the development of practical products and processes. Technological inventions and innovations can have wide-ranging applications for, and impacts on, society and the environment. The purpose of exploring an application is to research a particular technological invention or innovation to determine how it works, how it is used, and how it may affect society and the environment. The skills of researching, communicating, and evaluating may be useful in an activity that involves exploring an application.

A5.1 Research Skills

The following skills are involved in many types of research. Some of these skills will help you research issues only, while some will help you research issues or applications. Refer to this section when you have questions about any of the following skills and processes.

DEFINING THE ISSUE

When exploring an issue, the first step in understanding the issue is to explain why it exists, the problems associated with it, and, if applicable, the individuals or groups, also known as stakeholders, that are involved in it. The issue includes information about the role a person takes when thinking about an issue as well as a description of whom your audience will be. You could brainstorm questions involving Who? What? Where? When? Why? and How? Develop background information on the issue by clarifying facts and concepts, and identifying relevant attributes, features, or characteristics of the problem.

RESEARCHING

When beginning your research for both issues and applications, you need to formulate a research question that helps to limit, narrow, or define the scope of your research. You then need to develop a plan to find reliable and relevant sources of information. This includes outlining the stages of your research: gathering, sorting, evaluating, selecting, and integrating relevant information. You should gather information from a variety of sources if possible (for example, print, web, and personal interviews).

As you collect information, do your best to ensure that the information is reliable, accurate, and current. Avoid biased opinions: those that are not supported by or that ignore credible evidence. It is important to ensure that the information you have gathered addresses all aspects of the issue or application you are researching.

IDENTIFYING ALTERNATIVES

When exploring an issue, examine the situation and think of as many alternative solutions as you can. Be creative about combining the solutions. At this point, it does not matter if the solutions seem unrealistic. To analyze the alternatives, you should examine the issue from a variety of perspectives. Stakeholders may bring different viewpoints to an issue and these may influence their position on the issue. Brainstorm or hypothesize how different stakeholders would feel about your alternatives.

ANALYZING THE ISSUE

An important part of exploring an issue is analyzing the issue. First, you should establish criteria for evaluating your information to determine its relevance and significance. You can then evaluate your sources, determine what assumptions may have been made, and assess whether you have enough information to make your decision.

To effectively analyze an issue you should

- establish criteria for determining the relevance and significance of the data you have gathered
- evaluate the sources of information
- identify and determine what assumptions have been made
- challenge unsupported evidence
- evaluate the alternative solutions, possibly by conducting a risk-benefit analysis

Once the issue has been analyzed, you can begin to evaluate the alternative solutions. You may decide to carry out a risk-benefit analysis—a tool that enables you to look at each possible result of a proposed action and helps you make a decision (see Section A5.2 for more information.)

DEFENDING A DECISION

After analyzing your information on your issue, you can answer your research question and take an informed position or draw a conclusion on the issue. If you are working as a group, this is the stage where everyone gets a chance to share ideas and information gathered about the issue. Then the group needs to evaluate all the possible alternatives and decide on their preferred solution based on the criteria.

Your position on the issue or conclusion must be justified using supporting information that you have researched. You should be able to defend your position to people with different perspectives. Ask yourself the following questions:

- Do I have supporting evidence from a variety of sources?
- Can I state my position clearly?
- Can I show why this issue is relevant and important to society?
- Do I have solid arguments (with solid evidence) supporting my position?
- Have I considered arguments against my position, and identified their faults?
- Have I analyzed the strong and weak points of each perspective?

COMMUNICATING

When exploring an issue, there are several things to consider when communicating your decision. You need to state your position clearly and take into consideration whom your audience is. You should always support your decision with objective data and a persuasive argument if possible. Be prepared to defend your position against any opposition.

You should be able to defend your solution in an appropriate format—debate, class discussion, speech, position paper, multimedia presentation, brochure, poster, video, etc.

When exploring an application you should communicate the “need or want” for the application (why the application was developed in the first place), the “how” (how the application/technology actually works), and the risks and benefits to society, individuals, and the environment. You should conclude with your “assessment” of the application.

EVALUATING

The final phase of your decision making when exploring an issue includes evaluating the decision itself and the process used to reach the decision. After you have made a decision, carefully examine the thinking that led to your decision.

Some questions to guide your evaluation include:

- What was my initial perspective on the issue? How has my perspective changed since I first began to explore the issue?
- How did we make our decision? What process did we use? What steps did we follow?
- To what extent were my arguments factually accurate and persuasively made?
- In what ways does our decision resolve the issue?
- What are the likely short- and long-term effects of the decision?
- To what extent am I satisfied with the final decision?
- What reasons would I give to explain our decision?
- If we had to make this decision again, what would I do differently?

A5.2 Risk-Benefit Analysis Model

Risk-benefit analysis is a tool used to organize and analyze information gathered in research, especially when exploring a socio-scientific issue. A thorough analysis of the risks and benefits associated with each alternative solution can help you decide on the best alternative.

- Research as many aspects of the situation as possible. Look at it from different perspectives.
- Collect as much evidence as you can, including reasonable projections of likely outcomes if the proposal is adopted.
- Classify every individual potential result as being either a benefit or a risk.
- Quantify the size of the potential benefit or risk (perhaps as a dollar figure, or a number of lives affected, or on a scale of 1 to 5).
- Estimate the probability (percentage) of that event occurring.
- By multiplying the size of a benefit (or risk) by the probability of its happening, you can calculate a probability value for each potential result.
- Total the probability values of all the potential risks, and all the potential benefits.
- Compare the sums to help you decide whether to accept the proposed action.

A6 Math Skills

A6.1 Scientific Notation

It is difficult to work with very large or very small numbers when they are written in common decimal notation. Usually it is possible to accommodate such numbers by changing the SI prefix so that the number falls between 0.1 and 1000. For example, 237 000 000 mm can be expressed as 237 km, and 0.000 000 895 kg can be expressed as 0.895 mg. However, this prefix change is not always possible, either because an appropriate prefix does not exist or because it is essential to use a particular unit of measurement in a calculation. In these cases, the best method of dealing with very large and very small numbers is to write them using scientific notation. Scientific notation expresses a number by writing it in the form $a \times 10^n$, where $1 \leq |a| < 10$ and the digits in the coefficient a are all significant. **Table 1** shows situations where scientific notation would be used.

Table 1 Examples of Scientific Notation

Expression	Common decimal notation	Scientific notation
"124.5 million kilometres"	124 500 000 km	1.245×10^8 km
"154 thousand picometres"	154 000 pm	1.54×10^5 pm
"602 sextillion molecules"	602 000 000 000 000 000 000 000 molecules	6.02×10^{23} molecules

To multiply numbers in scientific notation, multiply the coefficients and add the exponents. To divide numbers in scientific notation, divide the coefficients and subtract the exponents. The answer is always expressed in scientific notation. Note that the coefficient should always be between 1 and 10. For example,

$$\begin{aligned}(4.73 \times 10^5\ \text{m})(5.82 \times 10^7\ \text{m}) &= 27.5 \times 10^{12}\ \text{m}^2 \\ &= 2.75 \times 10^{13}\ \text{m}^2\end{aligned}$$

$$\frac{(6.4 \times 10^6\ \text{m})}{(2.2 \times 10^3\ \text{s})} = 2.9 \times 10^3\ \text{m/s}$$

When evaluating exponents, the following rules apply:

$$x^a \cdot x^b = x^{a+b} \qquad (xy)^b = x^b y^b$$

$$\frac{x^a}{x^b} = x^{a-b} \qquad \left(\frac{x}{y}\right)^b = \frac{x^b}{y^b}$$

$$(x^a)^b = x^{ab}$$

SCIENTIFIC NOTATION WITH CALCULATORS

On many calculators, scientific notation is entered using a special key, labelled EXP or EE. This key includes "× 10" from the scientific notation; you need to enter only the exponent. For example, to enter

7.5×10^4 press 7.5 EXP 4

3.6×10^{-3} press 3.6 EXP +/– 3

Depending on the type of calculator you have, +/− may need to be entered after the relevant number.

A6.2 Uncertainty in Measurements

There are two types of quantities that are used in science: exact values and measurements. Exact values include defined quantities (1 m = 100 cm) and counted values (5 beakers or 10 trials). Measurements, however, are not exact because there is some uncertainty or error associated with every measurement.

SIGNIFICANT DIGITS

The certainty of any measurement is communicated by the number of significant digits in the measurement. In a measured or calculated value, significant digits are the digits that are known reliably, or for certain, and include the last digit that is estimated or uncertain. Significant digits include all digits correctly reported from a measurement.

Follow these rules to decide if a digit is significant:

1. All non-zero digits are significant.
2. If a decimal point is present, zeros to the left of other digits (leading zeros) are not significant.
3. If a decimal point is not present, zeros to the right of the last non-zero digit (trailing zeros) are not significant.
4. Zeros placed between other digits are always significant.
5. Zeros placed after other digits to the right of a decimal point are significant.
6. When a measurement is written in scientific notation, all digits in the coefficient are significant.
7. Counted and defined values have infinite significant digits.

Table 2 shows examples of significant digits.

Table 2 Certainty in Significant Digits

Measurement	Number of significant digits
32.07 m	4
0.0041 g	2
5×10^5 kg	1
7002 N • m	4
6400 s	2
6.0000 A	5
204.0 cm	4
10.0 kJ	3
100 people (counted)	infinite

An answer obtained by multiplying and/or dividing measurements is rounded to the same number of significant digits as the measurement with the fewest significant digits. For example, using a calculator to solve the following equation,

$$77.8 \text{ km/h} \times 0.8967 \text{ h} = 69.76326 \text{ km}$$

However, the certainty of the answer is limited to three significant digits, so the answer is rounded up to 69.8 km. The same applies to scientific notation. For example,

$$(5.5 \times 10^4) + (4.236 \times 10^4) = 9.7 \times 10^4$$

ROUNDING

When adding or subtracting measurements of different precisions, the answer is rounded to the same precision as the least precise measurement. For example, using a calculator,

$$11.7 \text{ cm} + 3.29 \text{ cm} + 0.542 \text{ cm} = 15.532 \text{ cm}$$

The answer must be rounded to 15.5 cm because the first measurement limits the precision to a tenth of a centimetre.

Follow these rules to round answers to calculations:

1. When the first digit to be dropped is 4 or less, the last digit retained should not be changed.
   3.141 326 rounded to 4 digits is 3.141
2. When the first digit to be dropped is greater than 5, or if it is a 5 followed by at least one digit other than zero, the last digit retained is increased by 1 unit.
   2.221 682 rounded to 5 digits is 2.2217
   4.168 501 rounded to 4 digits is 4.169
3. When the first digit discarded is 5 followed by only zeros, the last digit retained is increased by 1 if it is odd, but not changed if it is even.
   2.35 rounded to 2 digits is 2.4
   2.45 rounded to 2 digits is 2.4
   −6.35 rounded to 2 digits is −6.4

MEASUREMENT ERROR

There are two types of measurement error: random error and systematic error. Random error results when an estimate is made to obtain the last significant digit for any measurement. The size of the random error is determined by the precision of the measuring instrument. For example, when measuring length with a measuring tape, it is necessary to estimate between the marks on the measuring tape. If these marks are 1 cm apart, the random error will be greater and the precision will be less than if the marks are 1 mm apart. Such errors can be reduced by taking the average of several readings.

Systematic error is associated with an inherent problem with the measuring system, such as the presence of an interfering substance, incorrect calibration, or room conditions. For example, if a balance is not zeroed at the beginning, all measurements will have a systematic error; using a slightly worn metre stick will also introduce a systematic error. Such errors are reduced by adding or subtracting the known error, calibrating the instrument, or performing a more complex investigation.

PRECISION AND ACCURACY

"Precision" and "accuracy" are two other terms used to describe how close a measurement is to a true value. The precision of a measurement depends upon the gradations of the measuring device. Precision is the place value of the last measurable digit. For example, a measurement of 12.74 cm is more precise than a measurement of 127.4 cm because the first value was measured to hundredths of a centimetre, whereas the latter was measured to tenths of a centimetre.

No matter how precise a measurement is, it still may not be accurate. Accuracy refers to how close a value is to its accepted value. An accurate measurement has a low uncertainty. **Figure 1** shows an analogy between precision and accuracy: the positions of golf balls on a golf course.

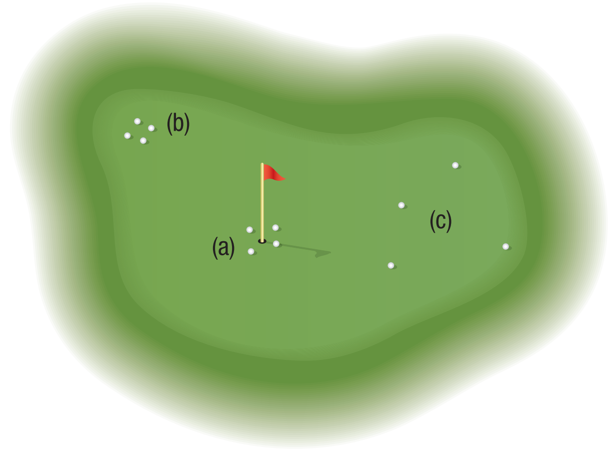


Figure 1 In (a) the results are precise and accurate, in (b) they are precise but not accurate, and in (c) they are neither precise nor accurate.

How certain you are about a measurement depends on two factors: the precision of the instrument used and the size of the measured quantity. More precise instruments give more certain values. For example, a mass measurement of 13 g is less precise than a measurement of 12.76 g; you are more certain about the second measurement than the first. Certainty also depends on the size of the measurement. For example, consider the measurements 0.4 cm and 15.9 cm; both have the same precision. However, if the measuring instrument is precise to ± 0.1 cm, the first measurement is 0.4 ± 0.1 cm (0.3 cm or 0.5 cm) for an error of 25 %, whereas the second measurement could be 15.9 ± 0.1 cm (15.8 cm or 16.0 cm) for an error of 0.6 %. For both factors—the precision of the instrument used and the value of the measured quantity—the more digits there are in a measurement, the more certain you are about the measurement.

REPORTING DATA INVOLVING MEASUREMENTS

A formal report of an experiment involving measurements should include an analysis of uncertainty, percentage uncertainty, and percentage error or percentage difference. Uncertainty is often assumed to be plus or minus half of the smallest division of the scale on the instrument; for example, the estimated uncertainty of 15.8 cm is ± 0.05 cm or ± 0.5 mm.

Whenever calculations involving addition or subtraction are performed, the uncertainties accumulate. Thus, to find the total uncertainty, the individual uncertainties must be added. For example,

$$(34.7\text{ cm} \pm 0.05\text{ cm}) - (18.4\text{ cm} \pm 0.05\text{ cm}) = 16.3\text{ cm} \pm 0.10\text{ cm}$$

Percentage uncertainty is calculated by dividing the uncertainty by the measured quantity and multiplying by 100. Use your calculator to prove that 28.0 cm ± 0.05 cm has a percentage uncertainty of ± 0.18 %.

Whenever calculations involving multiplication or division are performed, the percentage uncertainties must be added. If desired, the total percentage uncertainty can be converted back to uncertainty. For example, consider the area of a certain rectangle:

$$\begin{aligned} A &= lw \\ &= (28.0\text{ cm} \pm 0.18\ \%)(21.5\text{ cm} \pm 0.23\ \%) \\ &= 602\text{ cm}^2 \pm 0.41\ \% \\ A &= 602\text{ cm}^2 \pm 2.5\text{ cm}^2 \end{aligned}$$

Percentage error can be determined only if it is possible to compare a measured value with that of the most commonly accepted value. The equation is

$$\%\text{ error} = \frac{\text{measured value} - \text{accepted value}}{\text{accepted value}} \times 100$$

Percentage difference is useful for comparing two measurements when the true measurement is not known or for comparing a measured value to a predicted value. The percentage difference is calculated as

$$\%\text{ difference} = \frac{\text{measured value} - \text{predicted value}}{\text{predicted value}} \times 100$$

A6.3 Use of Units

When solving problems in science it is important to denote the units that go with a numerical value. 170 as an answer is unacceptable since there are no units. 170 g/mL denotes a density, 170 °C denotes a temperature, 170 K denotes a temperature in kelvins, and 170 kPa denotes a pressure. Understanding and placing units with a value gives the proper context of the value.

You can also identify a formula by looking at the units. For instance, if a density of 9.01 g/cm^3 is given, you can note that the density units have grams (mass) divided by cm^3 (volume), so the formula for density is mass divided by volume or $D = M/V$.

A6.4 Mathematical Equations

Several mathematical equations involving geometry, algebra, and trigonometry can be applied in physics.

GEOMETRY

For a rectangle of length l and width w, the perimeter P and the area A are

$$P = 2l + 2w \quad \text{and} \quad A = lw$$

For a triangle of base b and altitude h, the area is

$$A = \frac{1}{2}bh$$

For a circle of radius r, the circumference C and the area A are

$$C = 2\pi r \quad \text{and} \quad A = \pi r^2$$

For a sphere of radius r, the area A and volume V are

$$A = 4\pi r^2 \quad \text{and} \quad V = \frac{4}{3}\pi r^3$$

For a right circular cylinder of height h and radius r, the area and volume are

$$A = 2\pi r^2 + 2\pi rh \quad \text{and} \quad V = \pi r^2 h$$

ALGEBRA

Pythagorean theorem: For calculating the length of a side of a right-angle triangle when two sides are given, where c is the hypotenuse and a and b are the other sides (**Figure 2**),

$$c^2 = a^2 + b^2$$

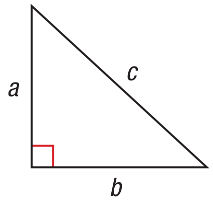


Figure 2 The Pythagorean theorem

Quadratic formula: Given a quadratic equation in the form $ax^2 + bx + c = 0$,

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

In this equation, the discriminant $b^2 - 4ac$ indicates the number of real roots of the equation. If $b^2 - 4ac < 0$, the quadratic function has no real roots. If $b^2 - 4ac = 0$, the quadratic function has one real root. If $b^2 - 4ac > 0$, the quadratic function has two real roots.

Example 1

A ball is launched from the roof of a building that is 40.0 m tall. If the ball is launched at an angle such that its vertical velocity is 10.0 m/s and its horizontal velocity is 17.3 m/s, determine the amount of time it takes the ball to reach the ground.

Given: $\Delta\vec{d}_y = -40.0\text{ m}$; $\vec{v}_{ix} = 12.2\text{ m/s}$; $\vec{v}_{iy} = 10.0\text{ m/s}$; $\vec{a}_y = -9.8\text{ m/s}^2$

Notice that in the given information, the vertical displacement and acceleration are listed as negative values. This indicates that both of these values are vectors that are pointing downward.

We can describe the vertical motion of the ball by the equation

$$\Delta\vec{d}_y = \vec{v}_{iy}\Delta t + \frac{1}{2}\vec{a}_y\Delta t^2$$

Required: Δt

Analysis: $\Delta\vec{d}_y = \vec{v}_{iy}\Delta t + \frac{1}{2}\vec{a}_y\Delta t^2$

Solution: $\Delta\vec{d}_y = \vec{v}_{iy}\Delta t + \frac{1}{2}\vec{a}_y\Delta t^2$

$$-40\text{ m} = (10.0\text{ m/s})\Delta t - \frac{1}{2}(9.8\text{ m/s}^2)\Delta t^2$$

$$0 = -4.9\Delta t^2 + 10.0\Delta t + 40.0$$

This is a quadratic equation for the variable Δt. We can now substitute values

$$a = -4.9,\ b = 10.0,\text{ and } c = 40.0$$

into the quadratic formula to determine the correct values for time.

$$\Delta t = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$\Delta t = \frac{-10.0 \pm \sqrt{(10.0)^2 - 4(-4.9)(40.0)}}{2(-4.9)}$$

$$\Delta t = \frac{-10.0 \pm 29.7}{-9.8}$$

$$\Delta t = -2.0\text{ s} \quad \text{or} \quad \Delta t = 4.0\text{ s}$$

Statement: We will choose the positive root; therefore, it takes the ball 4.0 s to reach the ground.

TRIGONOMETRY

The first application of trigonometry was to solve right-angle triangles. Trigonometry derives from the fact that for similar triangles, the ratio of corresponding sides will be equal.

The right-angle triangle in **Figure 3** shows the three sides of the triangle labelled with reference to the indicated angle α (alpha). Notice that the opposite side is opposite α, the hypotenuse side is the longest side of the triangle, and the adjacent side is beside the angle α. Trigonometry provides us with three ratios that can be used for solving problems:

$$\sin\alpha = \frac{opp}{hyp}$$

$$\cos\alpha = \frac{adj}{hyp}$$

$$\tan\alpha = \frac{opp}{adj}$$

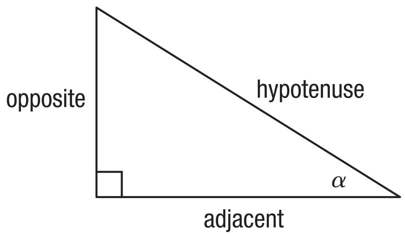


Figure 3 Right triangle

Figure 4 shows a right triangle where one interior angle and the length of one side are given. We can use the trigonometric ratios shown above to determine the length of the two unknown sides.

$$\sin 54^\circ = \frac{opp}{hyp} \qquad \cos 54^\circ = \frac{adj}{hyp}$$

$$\sin 54^\circ = \frac{Y}{2.3\text{ cm}} \qquad \cos 54^\circ = \frac{X}{2.3\text{ cm}}$$

$$Y = 2.3\text{ cm}\sin 54^\circ \qquad X = 2.3\text{ cm}\cos 54^\circ$$

$$Y = 1.9\text{ cm} \qquad X = 1.4\text{ cm}$$

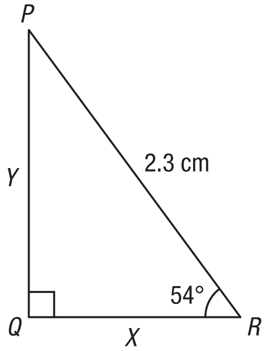


Figure 4 Right triangle

Figure 5 shows a right-angle triangle with an unknown interior angle β (beta). We can use one of the trigonometric ratios to solve for this interior angle, since we are given the length of two sides of this triangle.

$$\tan\beta = \frac{opp}{adj}$$

$$\tan\beta = \frac{X}{Y}$$

$$\beta = \tan^{-1}\left(\frac{2.6\text{ cm}}{7.3\text{ cm}}\right)$$

$$\beta = 20^\circ$$

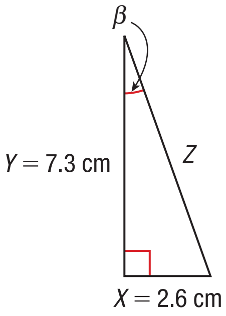


Figure 5 Right triangle

The length of the third side, Z, could be determined by using trigonometry, or by using the Pythagorean theorem. The Pythagorean theorem gives

$$Z^2 = X^2 + Y^2$$

$$Z = \sqrt{X^2 + Y^2}$$

$$Z = \sqrt{(2.6\ \mathrm{m})^2 + (7.3\ \mathrm{m})^2}$$

$$Z = 7.7\ \mathrm{m}$$

A6.5 Equations and Graphs

LINEAR EQUATIONS

Any straight line can be described by an equation of the form $y = mx + b$, where y is the dependent variable (on the y-axis) and x is the independent variable (on the x-axis). This equation is known as the slope-intercept form because m is the slope of the line on the graph and b is the y-intercept.

Figure 6 shows a linear (straight line) velocity-time graph. The slope of the line on this graph can be calculated using the following equation:

$$m = \frac{\text{rise}}{\text{run}} = \frac{(y_2 - y_1)}{(x_2 - x_1)}$$

where y_1 and x_1, and y_2 and x_2, are any two points on the line.

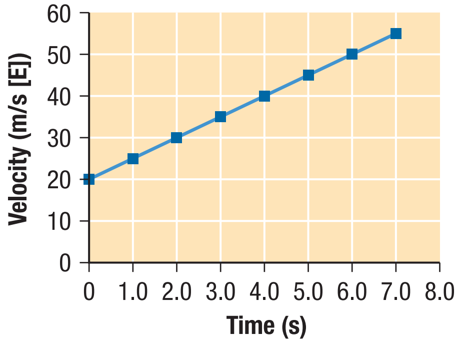


Figure 6 Velocity-time graph

From Figure 6, we can choose two points (1.0, 25) and (5.5, 47.5). We can now calculate the slope.

$$m = \frac{v_2 - v_1}{t_2 - t_1}$$

$$= \frac{(47.5 - 25.0)\ \mathrm{m/s}\ [\mathrm{E}]}{(5.5 - 1.0)\ \mathrm{s}}$$

$$= \frac{22.5\ \mathrm{m/s}\ [\mathrm{E}]}{4.5\ \mathrm{s}}$$

$$m = 5.0\ \mathrm{m/s^2}\ [\mathrm{E}]$$

The slope of the line is 5.0 m/s^2 [E]. This is a positive value, indicating a positive slope. A negative slope (decreasing from left to right) would have a negative value.

We can use a linear equation to describe the line on this graph. In general our equation will be of the form $y = mx + b$. In this example, since we have plotted velocity (v) on the y-axis and time (t) on the x-axis, our equation will be of the form $v = mt + b$. We have already calculated the slope of our straight line to be 5.0 m/s^2 [E]. The y-intercept for this graph can be determined by reading where the straight line crosses the y-axis. In this example the y-intercept has the value of 20 m/s [E]. As such, the equation describing the straight line will be $v = 5.0t + 20$. Note that this equation only includes numbers and variables. Metric units and directions are not included in algebraic equations.

We can confirm that our equation is correct by substituting a time value into it and checking the resulting velocity value. For example, at time $t = 4.0$ s our equation gives a velocity value of

$$v = 5.0(4.0) + 20$$

$$v = 40\ \mathrm{m/s}$$

As you can see, this corresponds to the value shown in our graph.

A6.6 Unit Analysis

Unit analysis is a useful tool to confirm that a calculation has been performed correctly or to convert units. Three quantities that are commonly measured in physics are mass (m), distance (Δd), and time (Δt). Note that the units of these measurements are all base units—kilogram (kg), metre (m), and second (s), respectively. In unit analysis, all units are expressed as base units.

After a while, unit analysis will become second nature. Consider a situation where you solve an equation in which time Δt is the unknown, and your final answer is $\Delta t = 2.1$ kg. You know that something clearly has gone wrong. Since time is measured in seconds (s), check your calculation to see where the error was made. It is important to note that while unit analysis can clearly point out when you have made an error, units that work out correctly do not necessarily indicate that your answer is correct. We can use unit analysis to confirm that the expression $\Delta d = v_{\mathrm{i}}t = \frac{1}{2}a\Delta t^2$ is mathematically valid.

To perform unit analysis, insert the appropriate units into the equation that you are analyzing. Place all units in brackets, and ignore any fractions in the equation that you are analyzing.

$$\Delta d = v_{\mathrm{i}}\Delta \mathrm{t} + \frac{1}{2}a\Delta t^2$$

$$(\mathrm{m}) = \frac{\mathrm{m}}{\cancel{\mathrm{s}}}(\mathrm{s}) + \frac{\mathrm{m}}{\cancel{\mathrm{s}}^2}(\cancel{\mathrm{s}}^2)$$

$$(\mathrm{m}) = (\mathrm{m}) + (\mathrm{m})$$

$$(\mathrm{m}) = (\mathrm{m})$$

Since both sides of the equation have the same units, metres (m), unit analysis has shown that this equation is mathematically valid.

You can also use unit analysis to convert from one unit to another. For example, to convert 95 km/h to m/s, kilometres must be changed to metres, and hours must be changed to seconds. Recall that 1 km = 1000 m, 1 h = 60 min, and

1 min = 60 s. The following three ratios can be written:

$$\frac{1000\text{ m}}{1\text{ km}} = 1 \qquad \frac{1\text{ h}}{60\text{ min}} = 1 \qquad \frac{1\text{ min}}{60\text{ s}} = 1$$

To convert from km/h to m/s we will use these three ratios strategically to cancel units that we do not want, and to keep units that we do want (m and s). Notice that these ratios can be inverted if necessary.

$$\frac{95\text{ km}}{\text{h}} = \frac{95\ \cancel{\text{km}}}{\cancel{\text{h}}} \times \frac{1000\text{ m}}{1\ \cancel{\text{km}}} \times \frac{1\ \cancel{\text{h}}}{60\ \cancel{\text{min}}} \times \frac{1\ \cancel{\text{min}}}{60\text{ s}}$$

Therefore,

$$\frac{95\text{ km}}{1\text{ h}} = \frac{95\,000\text{ m}}{3600\text{ s}}$$

$$= 26.4\text{ m/s, or } 26\text{ m/s (to two significant digits)}$$

Example 2

What will be the magnitude of the acceleration when a 2100 g object experiences a net force of magnitude 38.2 N?

First, convert grams to kilograms. Then, from Newton's second law, use the equation $F_{\text{net}} = ma$ to calculate acceleration.

Given: $m = 2100\text{ g}$; $F_{\text{net}} = 38.2\text{ N}$

Required: a

Analysis: $F_{\text{net}} = ma$

Solution:

$$\text{mass} = (2100\text{ g})\left(\frac{1\text{ kg}}{1000\text{ g}}\right)$$

$$\text{mass} = 2.1\text{ kg}$$

$$F_{\text{net}} = ma$$

$$a = \frac{F_{net}}{m}$$

$$= \frac{38.2\text{ N}}{2.1\text{ kg}}$$

$$a = 18\text{ N/kg}$$

It is more common to express acceleration in m/s^2, so we will use unit analysis to convert the units:

$$F_{\text{net}} = ma$$

$$[\text{N}] = \left[\frac{\text{kg}\cdot\text{m}}{\text{s}^2}\right]$$

$$a = \frac{18\text{N}}{\text{kg}}$$

$$= \frac{\left[\dfrac{18\ \cancel{\text{kg}}\cdot\text{m}}{\text{s}^2}\right]}{\cancel{\text{kg}}}$$

$$a = 18\text{ m/s}^2$$

Statement: The acceleration will be 18 m/s^2.

A6.7 Vectors

Several quantities in physics are vector quantities—quantities that have both magnitude (size) and direction. Understanding and working with vectors is crucial in solving many physics problems.

VECTOR SYMBOLS

A vector can be represented in a vector scale diagram, by an arrow or a directed line segment. The length of the arrow is proportional to the magnitude (size) of the vector, and the direction is the same as the direction of the vector. The tail of the vector is the initial point, and the tip of the vector is the end with the arrowhead. If the vector is drawn to scale, the scale should be indicated on the diagram, as should the direction north (**Figure 7**).

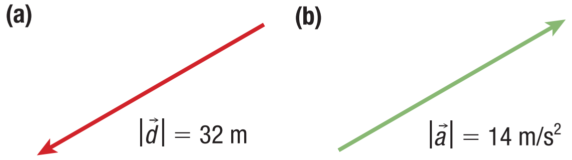


Figure 7 Examples of vector quantities: (a) displacement vector (scale: 1 cm = 10 m); (b) acceleration vector (scale: 1 cm = 5 m/s^2)

In this text, a vector quantity is indicated by an arrow above the letter representing the vector (for example, $\vec{A}$, $\vec{a}$, $\vec{F}$, $\vec{p}$, etc.). The magnitude of a vector $\vec{A}$ is indicated by simply A. The magnitude is always positive.

DIRECTIONS OF VECTORS

The directions of vectors are indicated in square brackets following the magnitude and units of the measurement. The four compass directions east, west, north, and south are indicated as [E], [W], [N], and [S]. Other examples are [down], [forward], [11.5° below the horizontal], [toward Earth's centre], and [W 24° N].

Figure 8 shows a vector drawn in the northwest quadrant of a Cartesian coordinate system. We would designate the direction of this vector as being [W 24° N]. This can be read as, "the vector initially pointed west, and was then rotated 24° toward north." Since the complementary angle of 24° is 66°, this direction could also be expressed as being [N 66° W]. Both of these directions are equally correct.

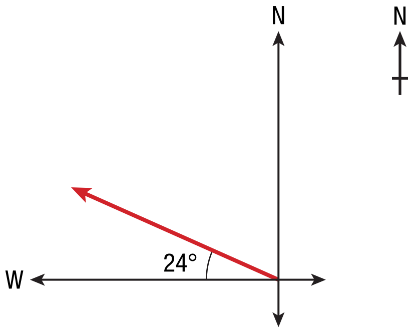


Figure 8 Locating the direction W 24° N. This represents a vector that was initially pointed west and was rotated 24° toward north.

VECTOR ADDITION

In arithmetic, 3 + 3 always equals 6. This is not always true when adding vector quantities. Vector addition must take into consideration the directions of the vectors. In this text we will use two methods to add vectors. Vector addition by scale diagram requires the use of a protractor and centimetre ruler to add vectors. Vector addition by components is a purely algebraic method for adding vectors.

Vector Addition: a Scale Diagram Approach

To add vector quantities by scale diagram, the arrows representing the vectors are drawn to scale, and are joined tip to tail. The resultant vector is drawn starting at the tail of the first vector and ending at the tip of the last vector added. Vector addition by scale diagram tends to be very simple for linear (straight line) problems. We will solve a linear and a two-dimensional problem in the following examples.

Example 3

Add the following two displacements by scale diagram:

$$\Delta\vec{d}_1 = 3.0\text{ m [E]},\ \Delta\vec{d}_2 = 5.0\text{ m [W]}$$

Note: When drawing a vector scale diagram, choose a scale that will produce a diagram that is approximately one-half to one full page in size. Be sure to indicate the scale and direction due north in your diagram.

Given: $\Delta\vec{d}_1 = 3.0$ m [E]; $\Delta\vec{d}_2 = 5.0$ m [W]

Required: $\Delta\vec{d}_T$

Analysis: $\Delta\vec{d}_T = \Delta\vec{d}_1 + \Delta\vec{d}_2$

Solution:

$$\begin{aligned}\Delta\vec{d}_T &= \Delta\vec{d}_1 + \Delta\vec{d}_2\\ &= 3.0\text{ m [E]} + 5.0\text{ m [W]}\end{aligned}$$

Figure 9 shows the total displacement, represented by the vector $\Delta\vec{d}_T$. From this diagram it is clear that the total displacement is represented by a vector 2.0 cm long pointing due west. Applying our scale this gives $\Delta\vec{d}_T = 2.0$ m [W].

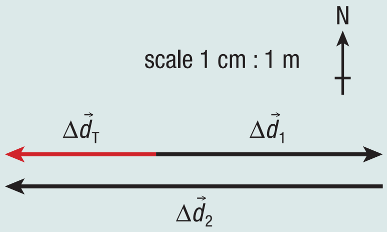


Figure 9 Two linear vectors added together using a scale diagram

Example 4

Add the following two displacement vectors by scale diagram:

$$\Delta\vec{d}_1 = 4.0\text{ m [E]},\ \Delta\vec{d}_2 = 5.0\text{ m [S 30° W]}$$

Figure 10 shows these two vectors joined tip to tail in a scale diagram. The length of the total displacement is measured to be 4.6 cm. Applying our scale, and using our protractor to measure the angle for the direction of this displacement vector, we get $\Delta\vec{d}_T = 4.6$ m [E 71° S].

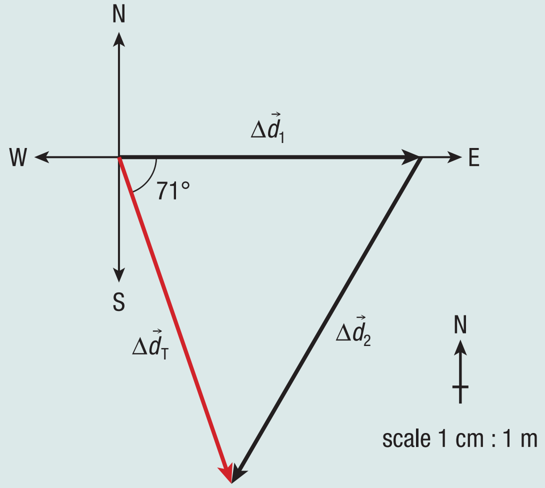


Figure 10 Two vectors added in two dimensions using a scale diagram

COMPONENTS OF VECTORS

Any two-dimensional vector can be broken down into two perpendicular components. **Figure 11** shows a displacement vector $\Delta\vec{d} = 15$ m [E 30° N] drawn on a Cartesian coordinate system.

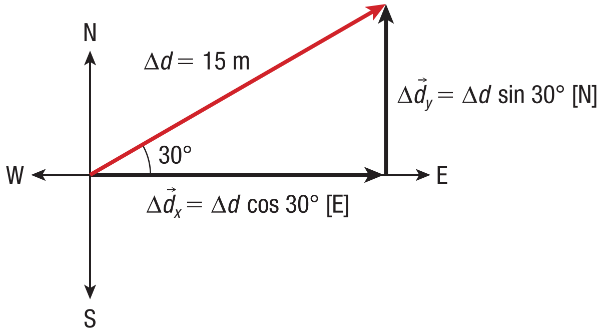

N
$\Delta d = 15$ m
$\Delta\vec{d}_y = \Delta d \sin 30°$ [N]
30°
W
E
$\Delta\vec{d}_x = \Delta d \cos 30°$ [E]
S

Figure 11 A vector broken down into two perpendicular components

This vector has been broken down into *x*- and *y*-components such that the *x*-component is drawn along the *x*-axis of the Cartesian coordinate system. When the two component vectors $\Delta\vec{d}_x$ and $\Delta\vec{d}_y$ are joined tip to tail as shown in the diagram, they will give the resultant vector $\Delta\vec{d} = 15$ m [E 30° N]. The directions of these two component vectors are clear from the diagram.

We can use trigonometry to determine the magnitude of each component vector. In this text we have recommended that you always draw *x*-components along the *x*-axis; this will ensure that each *x*-component vector will have a cosine term. Similarly, each *y*-component vector will have a sine term. As a result we can determine the magnitude and direction of our two component vectors as follows:

$$\cos 30° = \frac{\Delta d_x}{\Delta d} \qquad \sin 30° = \frac{\Delta d_y}{\Delta d}$$

$$\Delta d_x = \Delta d \cos 30° \qquad \Delta d_y = \Delta d \sin 30°$$

$$\Delta \vec{d}_x = \Delta d \cos 30° \text{ [E]} \qquad \Delta \vec{d}_y = \Delta d \cos 30° \text{ [N]}$$

$$\Delta \vec{d}_x = 15 \text{ m} \cos 30° \text{ [E]} \qquad \Delta \vec{d}_y = 15 \text{ m} \sin 30° \text{ [N]}$$

$$\Delta \vec{d}_x = 13 \text{ m [E]} \qquad \Delta \vec{d}_y = 7.5 \text{ m [N]}$$

- Vector addition is commutative; the order of addition does not matter: $\vec{A} + \vec{B} = \vec{B} + \vec{A}$
- Vector addition is associative. If more than two vectors are added, it does not matter how they are grouped: $(\vec{A} + \vec{B}) + \vec{C} = \vec{A} + (\vec{B} + \vec{C})$

Vector Addition: an Algebraic Approach

While vector addition by scale diagram is effective, it is not terribly precise. It can also become quite complex when adding more than two vectors. A purely algebraic method of adding vectors is far more precise. The method that we will use relies upon your knowledge of trigonometry and the Pythagorean theorem.

Example 5

Consider two vector forces acting on a single object. Determine the vector sum of these two forces.

$\vec{F}_1 = 10.5$ N [S] and $\vec{F}_2 = 14.0$ N [W]

Given: $\vec{F}_1 = 10.5$ N [S]; $\vec{F}_2 = 14.0$ N [W]

Required: $\vec{F}_T$

Analysis: $\vec{F}_T = \vec{F}_1 + \vec{F}_2$

Solution

Figure 12 shows the two force vectors joined tip to tail. Note that this is only a sketch; it is not drawn to scale. We can determine the magnitude of the resultant vector $\vec{F}_T$ using the Pythagorean theorem.

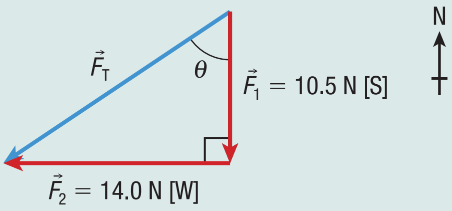


Figure 12 Determining the net force

$$\vec{F}_T = \vec{F}_1 + \vec{F}_2$$

$$F_T = \sqrt{F_1^2 + F_2^2}$$

$$= \sqrt{(10.5 \text{ N})^2 + (14.0 \text{ N})^2}$$

$$F_T = 17.5 \text{ N}$$

To determine the direction of the resultant vector, it is necessary to calculate the angle θ (theta) shown in Figure 12.

We can calculate this angle by using the tangent function.

$$\tan\theta = \frac{F_2}{F_1}$$

$$\theta = \tan^{-1}\left(\frac{14.0 \text{ N}}{10.5 \text{ N}}\right)$$

$$\theta = 53°$$

So, the final resultant vector can be expressed as

$$\vec{F}_T = 17.5 \text{ N [S } 53° \text{ W]}$$

Often we are required to add vectors together that are not perpendicular to each other. We can still do this algebraically. The method is known as vector addition by components. The goal is to take a question and convert it into the sample problem that we have just solved; that is, to take a general two-dimensional vector problem and convert it into a problem where we have two perpendicular vectors. To add any number of vectors by components, use the following steps:

1. Draw a Cartesian coordinate system.
2. Draw each vector to be added on the Cartesian coordinate system starting at the origin.
3. Break each vector down into *x*- and *y*-components such that the *x*-component is drawn along the *x*-axis.
4. Determine the sum of the *x*-components by adding all the individual *x*-components.
5. Determine the sum of the *y*-components by adding all the individual *y*-components.
6. Draw a sketch showing the overall *x*- and *y*-component vectors joined tip to tail.
7. Determine the magnitude and direction of the resultant vector by using the Pythagorean theorem and tangent function.

Example 6

Determine the vector sum of the two following displacements: $\Delta\vec{d}_1 = 25$ m [N 40° W], $\Delta\vec{d}_2 = 35$ m [S 20° E]

Required: d_T

Analysis: $\Delta\vec{d}_T = \Delta\vec{d}_1 + \Delta\vec{d}_2$

Solution: $\Delta\vec{d}_T = \Delta\vec{d}_1 + \Delta\vec{d}_2$

$\Delta\vec{d}_T = 25\text{ m [N 40° W]} + 35\text{ m [S 20° E]}$

Figure 13 shows our two displacement vectors drawn on a Cartesian coordinate system. Each vector is drawn from the origin, and has an *x*-component, which is drawn along the *x*-axis.

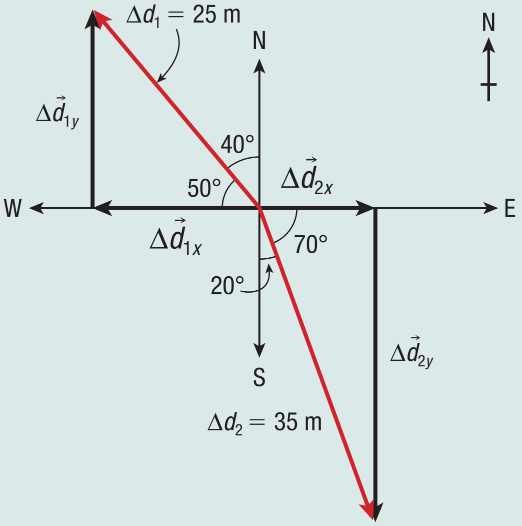


Figure 13 Two vectors and their components drawn on a Cartesian coordinate system

Calculate the vector sum of the *x*-components.

$$
\begin{aligned}
\Delta\vec{d}_{Tx} &= \Delta\vec{d}_{1x} + \Delta\vec{d}_{2x} \\
&= \Delta d_1 \cos 50° \text{ [W]} + \Delta d_2 \cos 70° \text{ [E]} \\
&= (25\text{ m})(\cos 50°)\text{ [W]} + (35\text{ m})(\cos 70°)\text{ [E]} \\
&= 16.1\text{ m [W]} + 12.0\text{ m [E]} \\
&= 16.1\text{ m [W]} - 12.0\text{ m [W]} \\
\Delta\vec{d}_{Tx} &= 4.10\text{ m [W]}
\end{aligned}
$$

Calculate the vector sum of the *y*-components.

$$
\begin{aligned}
\Delta\vec{d}_{Ty} &= \Delta\vec{d}_{1y} + \Delta\vec{d}_{2y} \\
&= \Delta d_1 \sin 50° \text{ [N]} + \Delta d_2 \sin 70° \text{ [S]} \\
&= (25\text{ m})(\sin 50°)\text{ [N]} + (35\text{ m})(\sin 70°)\text{ [S} \\
&= 19.2\text{ m [N]} + 32.9\text{ m [S]} \\
&= -19.2\text{ m [S]} + 32.9\text{ m [S]} \\
\Delta\vec{d}_{Ty} &= 13.7\text{ m [S]}
\end{aligned}
$$

Figure 14 shows a sketch of the overall *x*- and *y*-component vectors joined tip to tail.

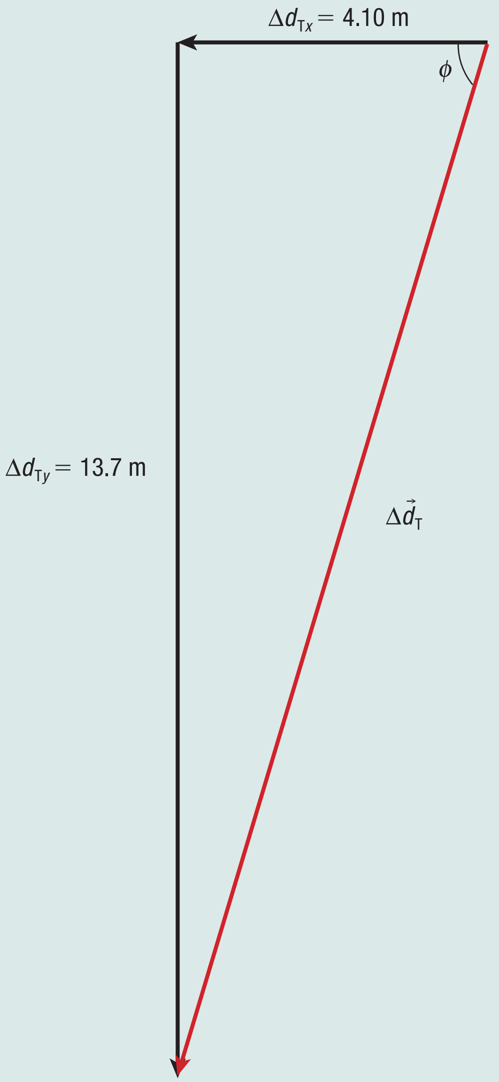


Figure 14 Adding the overall *x*- and *y*-components

We can now use the Pythagorean theorem to determine the magnitude of the resultant vector and the tangent function to determine its direction.

$$
\begin{aligned}
\Delta d_T{}^2 &= \Delta d_{Tx}{}^2 + \Delta d_{Ty}{}^2 \\
\Delta d_T &= \sqrt{\Delta d_{Tx}{}^2 + \Delta d_{Ty}{}^2} \\
\Delta d_T &= \sqrt{(4.10\text{ m})^2 + (13.7\text{ m})^2} \\
\Delta d_T &= 14\text{ m}
\end{aligned}
$$

$$
\begin{aligned}
\tan\phi &= \frac{\Delta d_{Ty}}{\Delta d_{Tx}} \\
\phi &= \tan^{-1}\left(\frac{13.7\text{ m}}{4.10\text{ m}}\right) \\
\phi &= 73°
\end{aligned}
$$

So $\Delta\vec{d}_T = 14$ m [W 73° S]

A7 Choosing Appropriate Career Pathways

Often, one of the most difficult tasks in high school is deciding what career path to follow after graduation. The science skills and concepts presented in this book will be of benefit to many careers, whether you are planning a career in scientific research (such as research geneticist or astrophysicist) or in areas related to science (such as environmental lawyer, pharmaceutical sales rep, or electrician). The strong critical-thinking and problem-solving skills that are emphasized in science programs are a valuable asset for any career.

Career Links and Pathways

Throughout this textbook you will have many opportunities to explore careers related to your studies in physics. The Career Links icons found in the margins indicate that you can learn more about these careers on the Nelson Science website. At the end of each chapter you will also find a Career Pathways feature that illustrates sample educational pathways for some of the careers mentioned.

It is wise to begin researching academic requirements as early as possible. Understanding the options available to pursue a particular career will help you make decisions on whether to attend university or college, and which program of study you should take. In addition, understanding the terminology used by universities and colleges will play an integral role in planning your future.

University and College Programs

Undergraduate university programs generally lead to a three-year general bachelor degree or a four-year honours bachelor degree. These degree designations begin with a “B” followed by the area of specialization; for example, a B.Sc. (Hons.) indicates an Honours Bachelor of Science degree. These degrees can lead to employment or to further education in Masters or Doctorate postgraduate programs. The length of postgraduate degrees generally varies from one to four years.

College programs typically fall into three categories: one-year certificates, two-year diplomas, and three-year advanced diplomas. Certificates and diplomas can lead directly to employment opportunities or to graduate certificate programs. In some programs, there are “transfer agreements” with universities, which allow college graduates to enter university programs with advanced standing toward a university degree.

Pathways in Physics

The Career Pathways graphic organizer illustrates possible pathways to follow after high school. Certain pathways lead to careers via university while others may lead to careers via college. Look at **Figure 1** below. The pathways of two students are highlighted. Student A wishes to become a research scientist and must complete the Grade 11 and 12 University Physics courses (along with other prerequisites) and enter an undergraduate university program. Student A must obtain a Bachelor of Science degree, and then continue on to further education in Masters and Doctorate programs before becoming a research scientist.

Student B wishes to become a Geographic Information System (GIS) analyst and must complete the Grade 11 University Physics course (along with other prerequisites) and enter an undergraduate university program. Student B must obtain a Bachelor of Arts degree, for example in Geography, and then continue on to a college for a graduate certificate program in GIS before becoming a GIS analyst.

Planning for Your Future

Planning ahead for your educational and career paths will provide a rewarding future. You should consult your guidance counsellors for specific advice on career planning and which courses you should take in high school. Take the time to research university and college websites for specific program information as these sites will provide the prerequisite information and, most often, career planning advice. While it may seem overwhelming at times, utilizing as many resources as possible will help alleviate some of the stress in planning your future. 🌐

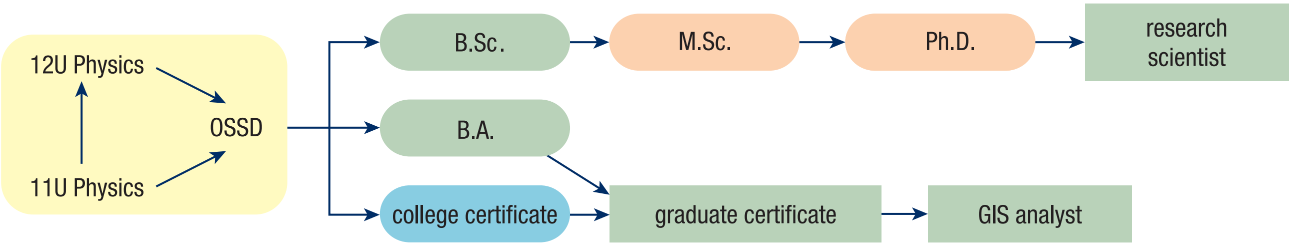


Figure 1 This graphic organizer shows pathways to several careers that benefit from courses in physics.

APPENDIX B REFERENCE

Throughout *Nelson Physics 11* and in this reference section, we have attempted to be consistent in the presentation and usage of units. As far as possible, the text uses the International System of Units (SI). However, some other units have been included because of their practical importance, wide usage, or use in specialized fields.

Nelson Physics 11 has followed the most recent Canadian Metric Practice Guide (CAN/CSA-Z234.1-00), published in 2000 and updated in 2003 by the Canadian Standards Association.

Table 1 SI Base Units

Quantity	Symbol	Unit name	Symbol
amount of substance	n	mole	mol
Celsius temperature	t	Celsius	°C
electric current	I	ampere	A
length	L, l, h, d, w	metre	m
luminous intensity	I_v	candela	cd
mass	m	kilogram	kg
thermodynamic temperature	T	Kelvin	K
time	t	second	s

Table 2 Some SI-Derived Units

Quantity	Symbol	Unit	Unit symbol	SI base unit
acceleration	$\vec{a}$	metre per second per second	m/s^2	m/s^2
area	A	square metre	m^2	m^2
density	ρ, D	kilogram per cubic metre	kg/m^3	kg/m^3
displacement	$\Delta\vec{d}$	metre	m	m
electric charge	Q, q	coulomb	C	A·s
electric field	E	volt per metre	V/m	kg·m/A·s^3
electric field intensity	E	newton per coulomb (Tesla)	N/C, T	kg/A·s^2
electric potential	V	volt	V	kg·m^2/A·s^3
electric resistance	R	ohm	Ω	kg·m^2/A^2·s^3
energy	E, E_k, E_p	joule	J	kg·m^2/s^2
force	F	newton	N	kg·m/s^2
frequency	f	hertz	Hz	s^{-1}
heat	Q	joule	J	kg·m^2/s^2
magnetic field	B	weber per square metre (Tesla)	T	kg/A·s^2
magnetic flux	Φ	weber	Wb	kg·m^2/A·s^2
momentum	p	kilogram metre per second	kg·m/s	kg·m/s
period	T	second	s	s
power	P	watt	W	kg·m^2/s^3
pressure	p	newton per square metre	N/m^2	kg/m·s^2
speed	v	metre per second	m/s	m/s
velocity	$\vec{v}$	metre per second	m/s	m/s
volume	V	cubic metre	m^3	m^3
wavelength	λ	metre	m	m
weight	W, w	newton	N	N, kg·m/s^2
work	W	joule	J	kg·m^2/s^2

Table 3 Numerical Prefixes

Powers and Subpowers of Ten		
Prefix	**Power**	**Symbol**
deca	10^1	da
hecto	10^2	h
kilo	10^3	k
mega	10^6	M
giga	10^9	G
tera	10^{12}	T
peta	10^{15}	P
exa	10^{18}	E
deci	10^{-1}	d
centi	10^{-2}	c
milli	10^{-3}	m
micro	10^{-6}	μ
nano	10^{-9}	n
pico	10^{-12}	p
femto	10^{-15}	f
atto	10^{-18}	a

Some Examples of Prefix Use

2000 metres $= 2 \times 10^3$ metres = 2 **kilo**metres or 2 km
0.27 metres $= 27 \times 10^{-2}$ metres = 27 **centi**metres or 27 cm
3 000 000 000 hertz $= 3 \times 10^9$ hertz = 3 **giga**hertz or 3 GHz

Table 4 The Greek Alphabet

Α	α	alpha
Β	β	beta
Γ	γ	gamma
Δ	δ	delta
Ε	ε	epsilon
Ζ	ζ	zeta
Η	η	eta
Θ	θ	theta
Ι	ι	iota
Κ	κ	kappa
Λ	λ	lambda
Μ	μ	mu
Ν	ν	nu
Ξ	ξ	xi
Ο	ο	omicron
Π	π	pi
Ρ	ρ	rho
Σ	σ	sigma
Τ	τ	tau
Υ	υ	upsilon
Φ	ϕ	phi
Χ	χ	chi
Ψ	ψ	psi
Ω	ω	omega

LEARNING **TIP**

SI Prefixes

Sometimes it is difficult to remember the metric prefixes. A mnemonic is a saying that helps you remember something. "King Henry Doesn't Mind Drinking Chocolate Milk" is a mnemonic for kilo, hecto, deca, metre, deci, centi, and milli. Another helpful hint is that mega (M) represents a million ($\times 10^6$) and tera (T) represents a trillion ($\times 10^{12}$). The first letters of the prefix and of what it represents are the same.

Table 5 Physical Constants

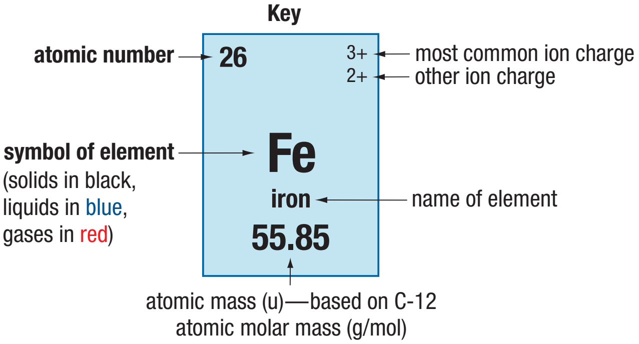
Quantity	Symbol	Approximate value
speed of light in a vacuum	c	3.00×10^{8} m/s
gravitational constant	G	6.67×10^{-11} N·m²/kg²
Coulomb's constant	k	9.00×10^{9} N·m²/C²
charge on electron	$-e$	-1.60×10^{-19} C
charge on proton	e	1.60×10^{-19} C
electron mass	m_e	9.11×10^{-31} kg
proton mass	m_p	1.673×10^{-27} kg
neutron mass	m_n	1.675×10^{-27} kg
atomic mass unit	u	1.660×10^{-27} kg
Planck's constant	h	6.63×10^{-34} J·s

Table 6 Data for Some Radioisotopes

Atomic number (Z)	Name	Symbol	Atomic mass (u)	Decay type	Half-life
1	tritium hydrogen-3	$^{3}_{1}\text{H}$	3.016 049	β^-	12.33 a
4	beryllium-7	$^{7}_{4}\text{Be}$	7.016 928	γ	53.29 d
6	carbon-11	$^{11}_{6}\text{C}$	11.011 433	β^+	20.385 min
6	carbon-14	$^{14}_{6}\text{C}$	14.003 242	β^-	5730 a
8	oxygen-15	$^{15}_{8}\text{O}$	15.003 065	β^+	122.24 s
11	sodium-22	$^{22}_{11}\text{Na}$	21.994 434	β^+, γ	2.6088 a
14	silicon-31	$^{31}_{14}\text{Si}$	30.975 362	β^-, γ	157.3 min
15	phosphorus-32	$^{32}_{15}\text{P}$	31.973 908	β^-	14.262 d
16	sulfur-35	$^{35}_{16}\text{S}$	34.969 033	β^-	87.51 d
19	potassium-40	$^{40}_{19}\text{K}$	39.96 400	β^-, β^+	1.28×10^{9} a
27	cobalt-60	$^{60}_{27}\text{Co}$	59.933 820	β^-, γ	5.2714 a
38	strontium-90	$^{90}_{38}\text{Sr}$	89.907 737	β^-	29.1 a
43	technetium-98	$^{98}_{43}\text{Tc}$	97.907 215	β^-, γ	4.2×10^{6} a
49	indium-115	$^{115}_{49}\text{In}$	114.903 876	β^-, γ	4.41×10^{14} a
53	iodine-131	$^{131}_{53}\text{I}$	130.906 111	β^-, γ	8.04 d
61	promethium-145	$^{145}_{61}\text{Pm}$	144.912 745	γ, α	17.7 a
75	rhenium-187	$^{187}_{75}\text{Re}$	186.955 746	β^-	4.35×10^{10} a
76	osmium-191	$^{191}_{76}\text{Os}$	190.960 922	β^-, γ	15.4 d
82	lead-210	$^{210}_{82}\text{Pb}$	209.984 163	β^-, γ, α	22.3 a
82	lead-211	$^{211}_{82}\text{Pb}$	210.988 734	β^-, γ	36.1 min
82	lead-212	$^{212}_{82}\text{Pb}$	211.991 872	β^-, γ	10.64 h

Atomic number (*Z*)	Name	Symbol	Atomic mass (u)	Decay type	Half-life
82	lead-214	$^{214}_{82}\text{Pb}$	213.999 798	β^-, γ	26.8 min
83	bismuth-211	$^{211}_{83}\text{Bi}$	210.987 254	α, β, β^-	2.14 min
84	polonium-210	$^{210}_{84}\text{Po}$	209.982 848	α, γ	138.376 d
84	polonium-214	$^{214}_{84}\text{Po}$	213.995 177	α, γ	0.1643 s
85	astatine-218	$^{218}_{85}\text{At}$	218.008 68	α, β^-	1.6 s
86	radon-222	$^{222}_{86}\text{Rn}$	222.017 571	α, γ	3.8235 s
87	francium-223	$^{223}_{87}\text{Fr}$	223.019 733	β^-, γ, α	21.8 min
88	radium-226	$^{226}_{88}\text{Ra}$	226.025 402	α, γ	1600 a
89	actinium-227	$^{227}_{89}\text{Ac}$	227.027 749	α, β^-, γ	21.773 a
90	thorium-228	$^{228}_{90}\text{Th}$	228.028 716	α, γ	1.9131 a
90	thorium-232	$^{232}_{90}\text{Th}$	232.038 051	α, γ	1.405×10^{10} a
91	protactinium-231	$^{231}_{91}\text{Pa}$	231.035 880	α, γ	3.276×10^{4} a
92	uranium-232	$^{232}_{92}\text{U}$	232.037 131	α, γ	68.9 a
92	uranium-233	$^{233}_{92}\text{U}$	233.039 630	α, γ	1.592×10^{5} a
92	uranium-235	$^{235}_{92}\text{U}$	235.043 924	α, γ	7.038×10^{8} a
92	uranium-236	$^{236}_{92}\text{U}$	236.045 562	α, γ	2.3415×10^{7} a
92	uranium-238	$^{238}_{92}\text{U}$	238.050 784	α, γ	4.468×10^{9} a
92	uranium-239	$^{239}_{92}\text{U}$	239.054 289	β^-, γ	23.50 min
93	neptunium-239	$^{239}_{93}\text{Np}$	239.052 932	β^-, γ	2.355 d
94	plutonium-239	$^{239}_{94}\text{Pu}$	239.052 157	α, γ	24 119 a
95	americium-243	$^{243}_{95}\text{Am}$	243.061 373	α, γ	7380 a
96	curium-245	$^{245}_{96}\text{Cm}$	245.065 484	α, γ	8500 a
97	berkelium-247	$^{247}_{97}\text{Bk}$	247.070 30	α, γ	1380 a
98	californium-249	$^{249}_{98}\text{Cf}$	249.074 844	α, γ	351 a
99	einsteinium-254	$^{254}_{99}\text{Es}$	254.088 02	α, β^-, γ	275.7 d
100	femium-253	$^{253}_{100}\text{Fm}$	253.085 174	α, γ	3.00 d
101	mendelevium-255	$^{255}_{101}\text{Md}$	255.091 07	α, γ	27 min
102	nobelium-255	$^{255}_{102}\text{No}$	255.093 24	α, γ	3.1 min
103	lawrencium-257	$^{257}_{103}\text{Lr}$	257.099 5	α	0.646 s
104	rutherfordium-261	$^{261}_{104}\text{Rf}$	261.108 69	α	65 s
105	dubnium-262	$^{262}_{105}\text{Db}$	262.113 76	α	34 s
106	seaborgium-263	$^{263}_{106}\text{Sg}$	263.116 2	α	0.9 s
107	bohrium-262	$^{262}_{107}\text{Bh}$	262.123 1	α	0.10 s
108	hassium-264	$^{264}_{108}\text{Hs}$	264.128 5	α	0.00008 s
109	meitnerium-266	$^{266}_{109}\text{Mt}$	266.137 8	α	0.0034 s

Nelson Physics 11


Key
atomic number
26
3+
2+
most common ion charge
other ion charge
symbol of element
(solids in black,
liquids in blue,
gases in red)
Fe
iron
name of element
55.85
atomic mass (u)—based on C-12
atomic molar mass (g/mol)

	1	2	3	4	5	6	7	8	9
1	1 1+ 1– **H** hydrogen 1.01								
2	3 1+ **Li** lithium 6.94	4 2+ **Be** beryllium 9.01							
3	11 1+ **Na** sodium 22.99	12 2+ **Mg** magnesium 24.31							
4	19 1+ **K** potassium 39.10	20 2+ **Ca** calcium 40.08	21 3+ **Sc** scandium 44.96	22 4+ 3+ **Ti** titanium 47.87	23 5+ 4+ **V** vanadium 50.94	24 3+ 2+ **Cr** chromium 52.00	25 2+ 4+ **Mn** manganese 54.94	26 3+ 2+ **Fe** iron 55.85	27 2+ 3+ **Co** cobalt 58.93
5	37 1+ **Rb** rubidium 85.47	38 2+ **Sr** strontium 87.62	39 3+ **Y** yttrium 88.91	40 4+ **Zr** zirconium 91.22	41 5+ 3+ **Nb** niobium 92.91	42 6+ **Mo** molybdenum 95.96	43 7+ **Tc** technetium (98)	44 3+ 4+ **Ru** ruthenium 101.07	45 3+ **Rh** rhodium 102.91
6	55 1+ **Cs** cesium 132.91	56 2+ **Ba** barium 137.33	57 3+ 2+ **La** lanthanum 138.91	72 4+ **Hf** hafnium 178.49	73 5+ **Ta** tantalum 180.95	74 6+ **W** tungsten 183.84	75 7+ **Re** rhenium 186.21	76 4+ **Os** osmium 190.23	77 4+ **Ir** iridium 192.22
7	87 1+ **Fr** francium (223)	88 2+ **Ra** radium (226)	89 3+ 2+ **Ac** actinium (227)	104 **Rf** rutherfordium (261)	105 **Db** dubnium (262)	106 **Sg** seaborgium (266)	107 **Bh** bohrium (264)	108 **Hs** hassium (277)	109 **Mt** meitnerium (268)
	Alkali metals	Alkaline earth metals							

6	58 3+ **Ce** cerium 140.12	59 3+ **Pr** praseodymium 140.91	60 3+ **Nd** neodymium 144.24	61 3+ **Pm** promethium (145)	62 3+ 2+ **Sm** samarium 150.36
7	90 4+ **Th** thorium 232.04	91 5+ 4+ **Pa** protactinium 231.04	92 6+ 4+ **U** uranium 238.03	93 5+ **Np** neptunium (237)	94 4+ 6+ **Pu** plutonium (244)

🟦 **Metals**
🟩 **Metalloids**
🟥 **Non-metals**
🟨 **Hydrogen**

Periodic Table of the Elements

Measured values are subject to change as experimental techniques improve. Atomic molar mass values in this table are based on IUPAC website values (2005 and 2007).

10	11	12	13	14	15	16	17	18	
								2 — **He** helium 4.00	1
			5 — **B** boron 10.81	6 — **C** carbon 12.01	7 3– **N** nitrogen 14.01	8 2– **O** oxygen 16.00	9 1– **F** fluorine 19.00	10 — **Ne** neon 20.18	2
			13 3+ **Al** aluminum 26.98	14 — **Si** silicon 28.09	15 3– **P** phosphorus 30.97	16 2– **S** sulfur 32.07	17 1– **Cl** chlorine 35.45	18 — **Ar** argon 39.95	3
28 2+ 3+ **Ni** nickel 58.69	29 2+ 1+ **Cu** copper 63.55	30 2+ **Zn** zinc 65.41	31 3+ **Ga** gallium 69.72	32 4+ **Ge** germanium 72.64	33 3– **As** arsenic 74.92	34 2– **Se** selenium 78.96	35 1– **Br** bromine 79.90	36 — **Kr** krypton 83.80	4
46 2+ 3+ **Pd** palladium 106.42	47 1+ **Ag** silver 107.87	48 2+ **Cd** cadmium 112.41	49 3+ **In** indium 114.82	50 4+ 2+ **Sn** tin 118.71	51 3+ 5+ **Sb** antimony 121.76	52 2– **Te** tellurium 127.60	53 1– **I** iodine 126.90	54 — **Xe** xenon 131.29	5
78 4+ 2+ **Pt** platinum 195.08	79 3+ 1+ **Au** gold 196.97	80 2+ 1+ **Hg** mercury 200.59	81 1+ 3+ **Tl** thallium 204.38	82 2+ 4+ **Pb** lead 207.2	83 3+ 5+ **Bi** bismuth 208.98	84 2+ 4+ **Po** polonium (209)	85 1– **At** astatine (210)	86 — **Rn** radon (222)	6
110 **Ds** darmstadtium (281)	111 **Rg** roentgenium (272)	112 **Cn** copernicium (285)	113 **Uut** ununtrium (284)	114 **Uuq** ununquadium (289)	115 **Uup** ununpentium (288)	116 **Uuh** ununhexium (291)	117 **Uus** ununseptium	118 **Uuo** ununoctium (294)	7
							Halogens	Noble gases	

63 3+ 2+ **Eu** europium 151.96	64 3+ **Gd** gadolinium 157.25	65 3+ **Tb** terbium 158.93	66 3+ **Dy** dysprosium 162.50	67 3+ **Ho** holmium 164.93	68 3+ **Er** erbium 167.26	69 3+ **Tm** thulium 168.93	70 3+ 2+ **Yb** ytterbium 173.05	71 2+ **Lu** lutetium 174.97	6
95 3+ 4+ **Am** americium (243)	96 3+ **Cm** curium (247)	97 3+ 4+ **Bk** berkelium (247)	98 3+ **Cf** californium (251)	99 3+ **Es** einsteinium (252)	100 3+ **Fm** fermium (257)	101 2+ 3+ **Md** mendelevium (258)	102 2+ 3+ **No** nobelium (259)	103 3+ **Lr** lawrencium (262)	7

APPENDIX C ANSWERS

These pages include numerical and short answers to chapter section questions and Chapter Self-Quiz, Chapter Review, Unit Self-Quiz, and Unit Review questions.

Unit 1

Are You Ready?, pp. 4–5

3. (a) m
   (b) s
   (c) m/s
9. (a) 18 m
   (b) 24 m
   (c) 17 m
10. (a) 56°
    (b) 74°
    (c) 56°
11. (a) 0.45963 km
    (b) 23 m/s
    (c) 100.0 km/h
    (d) 3.1557 × 10^7 s
12. (a) $a = 21$, $b = 7.3$
    (b) $c = 23$, $d = 19$
    (c) $e = 70$, $f = 57$

1.1 Questions, p. 13

3. 51 m [W]
4. 191 km [E]
5. (a) 13 m [W]
   (b) 7.0 m [W]
   (c) 21 m [N]
   (d) 0.0 km

1.2 Questions, p. 20

4. 3 m/s [W]
6. 38 m [S]
7. 0.58 s
8. 497 m/s [S]

1.3 Questions, p. 30

4. (a) 4.0 m/s^2 [E]
   (b) 3.5 m/s^2 [E]
   (c) 0.30 m/s^2 [E]
7. 1.3 m/s^2 [W]
8. 0.40 s
9. (a) 16.6 m/s [N]
10. 140 m/s^2

1.5 Questions, p. 39

1. 2.3 × 10^2 m [N]
2. (a) 1.7 m/s^2 [W]
   (b) 1.2 × 10^2 m [E]
3. 13 m/s [E]
4. A wins by 27 s.
5. 0.31 m/s^2
6. (a) 56 m/s^2 [up]
   (b) 2.2 × 10^2 m/s [up]

1.6 Questions, p. 43

3. (a) 9.8 m/s^2 [down]
   (b) 9.8 m/s^2 [down]
   (c) 9.8 m/s^2 [down]
4. (a) 0.55 s
   (b) 3.8 m/s [down]
5. (a) 3.3 × 10^2 m
   (b) 8.2 s
   (c) 16 s
6. 24 m/s [down]

Chapter 1 Self-Quiz, p. 51

1. (d)
2. (a)
3. (b)
4. (b)
5. (c)
6. (b)
7. (c)
8. (d)
9. F
10. T
11. F
12. F
13. F
14. T
15. F
16. F
17. T

Chapter 1 Review, pp. 52–57

1. (b)
2. (c)
3. (d)
4. (d)
5. (a)
6. (c)
7. (a)
8. (d)
9. (c)
10. F
11. F
12. T
13. F
14. F
15. T
16. F
17. F
18. T
19. (a) v
    (b) i
    (c) vi
    (d) ii
    (e) iii
    (f) iv
22. 2000 m [W]
23. 1750 m [E]
24. 4500 m [E]
25. 750 m [W]
26. 130 km [E]
27. 63 m/s
28. 45 m
29. 39 m/s [S]
30. 14 m/s [E]
31. 270 s
32. 997 m
35. 4.0 m/s^2 [E]
36. 13 m/s [W]
37. 2.74 ms
38. 86 km/h [S]
39. 5.9 m/s
40. 12 m [E]
41. 17 m [W]
42. (a) $\vec{v}_\mathrm{f}^{\,2} = \vec{v}_\mathrm{i}^{\,2} + 2\vec{a}\Delta d$
    (b) 4.3 m/s [down]
43. (a) 1.4 s
    (b) 14 m/s [down]
44. (b) 580 m [E]
45. (b) 18 m [S]
46. 2.0 m/s [E]
47. 24 m/s [N]
48. 19 m/s [W]
49. 12 h
50. 12 min
51. 8.3 m/s^2
52. 1.3 s
53. 10.6 m/s^2 [up]
54. 0.94 m/s^2
55. (a) From 0 s to 3.0 s,
    $\vec{a} = 0.33$ m/s^2 [E].
    From 3.5 s to 5.0 s,
    $\vec{a} = 0$ m/s^2.
    (b) 4.5 m [E]
56. (a) 14 m/s [S]
    (b) 20 m/s [S]
58. (a) about −2.5 m [E]
59. (a) 4.0 s
    (b) 90 m
60. 0.79 m/s^2
61. (a) 160 m [forward]
    (b) 100 km/h [forward]
63. 43 m
64. (a) 25 m
    (b) 4.5 s
67. (a) 2.0 m/s^2 [S]; −3.0 m/s^2 [S]
    $d = 21$ m
    (e) $\vec{d} = 9.0$ m [S]
68. (a) 1.0 s and 5.0 s

2.1 Questions, p. 65

4. 350 m [S 31° E]
5. 26 km [N 67° E]
7. 27 m [E 27° S]
8. (a) 9.5 m/s [E 69° S]
   (b) 11 m/s
9. (a) 87 km [N]
   (b) 5.2 × 10^2 km/h [N]

2.2 Questions, p. 75

1. (a) 13 km [W], 15 km [N]
   (b) 2.6 km [W], 15 km [S]
   (c) 36 km [E], 17 km [N]
2. 15 km [E 70° N]
3. 16 m [N 51° E]
4. 52.23 m [S 11° W]
5. 1.0 × 10 m [S 3° E]
6. (a) 11 km [W 36° N]
   (b) 37 m [E 30° N]
7. 15 m [N 32° W]
8. (a) 5.9 h
   (b) 12 km
9. 3.3 s, 4.2 m/s [N 17° E]

2.3 Questions, p. 81

2. 20 m, 2.00 s
3. (a) 90°
   (b) 45°
6. (a) 2.3 s
   (b) 3.9 s
7. The golfer was 41 m from the hole. The maximum height of the ball was 10 m.
8. 7.2 m

Chapter 2 Self-Quiz, p. 89

1. (b)
2. (a)
3. (c)
4. (b)
5. (a)
6. (c)
7. (d)
8. (b)
9. (b)
10. T
11. T
12. F
13. F
14. F
15. F
16. F

Chapter 2 Review, pp. 90–95

1. (b)
2. (d)
3. (b)
4. (a)
5. (b)
6. (c)
7. (c)
8. (a)
9. (a)
10. F
11. T
12. F
13. F
14. F
15. T
16. F
17. T
18. T
19. F
20. (a) ii
    (b) i
    (c) iv
    (d) v
    (e) iii
22. (a) 17 m [E 63° N]
    (b) 79 cm [W 56° S]
    (c) 44 km [N 27° W]
25. (a) 1 cm : 50 m
    (b) 1 cm : 150 km
    (c) 1 cm : 500 m
26. (a) 566 m [N 72° W]
    (b) 37 cm [S 22° E]
    (c) 7150 km [W 52° S]
31. (a) $\Delta\vec{d}_x = 16$ m [W]
    $\Delta\vec{d}_y = 49$ m [S]
    (b) $\Delta\vec{d}_x = 37$ km [E]
    $\Delta\vec{d}_y = 9.2$ km [N]
    (c) $\Delta\vec{d}_x = 91$ m [W]
    $\Delta\vec{d}_y = 13$ m [S]
32. (a) 5.8 m [W 30 ° S]
    (b) 19 m [E 16° N]
    (c) 71 km [W 26° N]
33. 5.4 m
34. 6.3 m
35. 8.1 m
36. 31 m [W 84° S]
37. (a) 18 s
    (b) 6.5 m/s [W 18° N]
    (c) 110 m

39. $v_x = 9.6$ m/s
$v_y = 11$ m/s
40. (a) 0.52 s
(b) 2.2 m
41. (a) 26.2 m/s
(b) 70.0 m
46. (b) 4.5 min
47. 1460 m [N 59° W]
48. 3260 m [W 57.5° S]
49. (a) 6.0 min
(b) 18 km/h [W 45° S]
50. 7.14 min
51. 8.0×10^2 m [N];
boat is travelling [N 43° E]
52. 25 m
53. 2.0×10^1 m/s [N 34° W]
54. 3.7 m/s
55. (a) [N]
(c) [N 17° W]
(d) 14 s
56. (a) 0.74 m
(b) 5.1 m/s
[73° above horizontal]
57. (a) 1.9 s
(b) 26 m
(c) 4.6 m
58. (a) 13 m/s
(b) 53°

Unit 1 Self-Quiz, pp. 98–99

1. (c)
2. (b)
3. (c)
4. (b)
5. (b)
6. (d)
7. (c)
8. (b)
9. (b)
10. (a)
11. (b)
12. (a)
13. (c)
14. (d)
15. (c)
16. (b)
17. (c)
18. (c)
19. F
20. F
21. T
22. F
23. F
24. F
25. T
26. T
27. F
28. F
29. F
30. F
31. T
32. F
33. F
34. F
35. F
36. T
37. F
38. T
39. T

Unit 1 Review, pp. 100–107

1. (c)
2. (c)
3. (b)
4. (d)
5. (b)
6. (c)
7. (d)
8. (b)
9. (d)
10. (b)
11. (b)
12. T
13. T
14. F
15. T
16. F
17. F
18. F
19. F
20. T
21. T
22. F
23. T
24. (a) vii
(b) iv
(c) v
(d) ii
(e) iii
(f) i
(g) vi
28. 1500 m [W]
29. 5870 m [W]
30. 1750 m [E]
31. 185 m [E]
32. 65 m/s
33. 29 m/s [E]
34. 9.1 m/s [E]
35. 1000 m
38. 1.8 m/s^2
39. 15.6 m/s
40. 1.13×10^{-2} s
41. 12 m [E]
42. (a) 1.7 s
(b) 17 m/s
44. (a) 86 m [N 82° E]
(b) 97 cm [S 67° E]
(c) 3190 km [W 22° S]
45. 1400 m
46. 2.6 m [N 18° E]
49. (a) $d_x = 20$ m [W]
$d_y = 80$ m [S]
(b) $d_x = 33$ m [E]
$d_y = 7.6$ m [N]
(c) $d_x = 41$ m [W]
$d_y = 88$ m [S]
50. (a) $d_T = 4.4$ m [W 25° S]
(b) $d_T = 7.8$ m [E 76° N]
(c) $d_T = 74$ m [W 12° N]
51. $d_T = 32$ m [W 41° S]
52. (a) 3.2×10^2 s
(b) 0.9 m/s [S 13° E]
(c) 2.9×10^2 m
54. $v_x = 10$ m/s
$v_y = 19$ m/s
55. (a) 0.49 s
(b) 2.6 m
56. 5.0 m/s^2 [down]
60. (a) 3.87 s
(b) 78.0 m
61. (a) 166 m
(b) 29.3 m/s or 105 km/h
66. 917 m [N], $d_T = 1550$ m [N 53.8° E]
67. 23 m
69. (a) 3.7 s
distance travelled = 76 m
maximum height = 17 m
(b) 18 m/s, 60°

Unit 2

Are You Ready?, pp. 110–111

2. (a) 1.6 m/s^2 [E]
(b) 7.9 m/s [down]
(c) 1.1 m/s^2 [N]
(d) 1.6 m/s^2 [E], 13.6 m/s [W]

3.1 Questions, p. 122

7. (a) 2.0×10 N [down]
(b) 610 N [down]
15. (a) 21 N [up]
(b) 6.0 N [left]
(c) 0 N

3.2 Questions, p. 129

13. (a) $F_1 = 17$ N [left]
$F_2 = 32$ N [up]
(b) $F_1 = 26$ N [right]
$F_2 = 54$ N [down]

3.3 Questions, p. 136

1. (a) 120 N [forward]
(b) 28 N [up]
2. (a) 4800 m/s^2 [E]
(b) 150 m/s^2 [forward]
3. (a) 1200 kg
(b) 5.5 kg
4. 130 N [downhill]
5. 1.5 kg
6. (a) 150 N [up]
(b) 2.6 m/s^2 [up]
7. 3.0 m/s^2
8. (b) 5900 N [E]
10. (a) 2.4 m/s^2 [left]
11. 3.4 s

3.4 Questions, p. 141

6. (b) 0.24 N [E] for toy car
0.24 N [W] for the ball
7. (a) 0.82 m/s^2 [W] for skater 1
1.1 m/s^2 [E] for skater 2
9. (a) 0.20 m/s^2 [left] for male astronaut
0.25 m/s^2 [right] for female astronaut

3.5 Questions, p. 147

1. (a) 65 N
(b) 65 N
(c) 65 N
2. (a) 260 N
(b) 1700 N [forward]
3. 7.7 s
4. (a) 650 N [forward]
(b) 650 N [forward]
(c) 1900 N [forward]
(d) 330 N [backwards]
5. 2.4 s
6. (a) 1.5 m/s^2 [forward]
(b) force sensor 1: 3.3 N
force sensor 2: 3.3 N
force sensor 3: 7.1 N
force sensor 4: 7.1 N
force sensor 5: 9.8 N
force sensor 6: 9.8 N
(c) 20 N [forward]
7. 0.23 m/s^2 [forward]
8. (a) 11 m/s
(b) 10 m/s
(c) 82 m

Chapter 3 Self Quiz, p. 153

1. (b)
2. (c)
3. (d)
4. (c)
5. (c)
6. (b)
7. (b)
8. (b)
9. T
10. F
11. F
12. F
13. T
14. T
15. F
16. T
17. F

Chapter 3 Review, pp. 154–159

1. (c)
2. (a)
3. (d)
4. (d)
5. (d)
6. (c)
7. (b)
8. (c)
9. F
10. F
11. T
12. T
13. F
14. F
15. T
16. T
17. F
18. (a) iii
(b) v
(c) ii
(d) i
(e) iv
19. 9.8 m/s^2
26. 37 000 N [N]
27. 36 200 N [W]
30. 87 N [left]
31. 20 N
33. (a) 140 N [forward]
(b) 6.1 N [down]
34. (a) 1.8 m/s^2 [N]
(b) 3.37 m/s^2 [up]
35. 4.0 m/s^2 [opposite direction of motion]
36. 0.26 N [opposite direction of motion]
37. 100 000 kg
38. 1.24×10^4 m/s^2 [S]
39. (a) 4.2 m/s^2 [right]
(b) 4.0 m/s^2 [right]
40. (a) 0.62 kg
(b) 0.67 kg
43. (a) 1.5 m/s^2
44. (a) 1.1 m/s^2
45. (a) 29 N
(b) 33 N
(c) 25 N
47. (a) 700 N
(b) 700 N
48. 440 N
49. 110 kg
50. 0.78 kg
51. 18 N
52. 220 N
53. (a) 1.5 m/s^2
(c) 23 m
54. 0.03 m/s^2 [left]
55. (a) 0 N in the vertical; 33 N [right] in the horizontal
(b) 0.39 m/s^2
56. (a) 13 N [down] in the vertical; 0 N in the horizontal
(b) 2.4 kg
57. (a) 48 N
(b) 12 N
58. (a) 125 N
(b) 100 N
59. (a) 1.6 m/s^2
(b) 120 N
(c) 120 N
60. (b) 1.8 m/s^2 [right] for the girl
0.83 m/s^2 [left] for the raft
61. (b) 1.2 m/s^2 [right] for the boy
1.3 m/s^2 [left] for the girl

62. (b) 90 N (c) 110 kg
63. (a) 1.4 m/s^2 (c) 9 kg
64. (a) 0.2 m/s^2 [left] for male; 0.25 m/s^2 [right] for female
65. (a) 1.4×10^5 N
    (b) 6.4×10^4 N
66. (a) 290 N on string A; 120 N on string B
    (b) 340 N on string A; 120 N on string B
    (c) 340 N on string A; 160 N on string B
67. 4.4 N for string A, 6.9 N for string B, 11 N for string C
68. 5.0 N for string A, 11 N for string B, 15 N for string C, 1.2 m/s^2 [right]
69. 9 N for string A, 20 N for string B, 24 N for string C
70. (a) 54 N
    (b) 110 N
    (c) 9.37 m

4.1 Questions, p. 167

5. (a) 74 kg
   (b) 89 N
6. (a) 1.03 N
7. (b) 310 N
   (c) 1.627 N/kg [down]
10. (a) 240 N
    (b) 290 N
    (c) 160 N

4.2 Questions, p. 172

3. (a) $\mu_S = 0.40$, $\mu_K = 0.30$
5. (a) 0.35
   (b) 330 N
   (c) 570 N
7. (a) 59 000 N
   (b) 47 000 N

4.3 Questions, p. 178

1. (a) 450 N
   (b) 1300 N
2. (a) 1.4
3. (a) 0.40
   (b) 12 N
   (c) $F_{Smax} = 37$ N, $F_T = 18$ N
4. (a) 0.30
5. (a) 18 N
   (b) 86 washers
   (d) 0.57 m/s^2 [right]
6. (a) 0.84
   (b) 0.76
7. (a) 0.21
   (b) 0.89 s
8. (a) i) 2.9 m/s^2 [forward]
       ii) 5.8 m
       iii) 0.39
9. 46 N [forward]
10. 0.11

Chapter 4 Self Quiz, p. 197

1. (b)
2. (d)
3. (b)
4. (d)
5. (a)
6. (d)
7. (a)
8. (c)
9. F
10. T
11. F
12. F
13. T
14. F
15. T
16. F
17. F
18. F
19. T
20. F

Chapter 4 Review, pp. 198–203

1. (c)
2. (b)
3. (a)
4. (d)
5. (a)
6. (b)
7. (d)
8. (c)
9. (c)
10. (d)
11. (c)
12. (a) iii
    (b) i
    (c) iv
    (d) ii
20. (d) 250 N
24. (b) 9.78 N/kg
28. 490 N
29. (a) 58 kg
    (b) 74 kg
    (c) 36 kg
31. (c) 74 N
33. (a) 0.22
34. (a) 12 N
    (b) 6.3 N
36. 17 N
37. (a) 190 N
    (b) 130 N
38. 0.68
45. 0.30
49. (a) 38 kg
    (b) 0.41
50. (a) 1.25 m/s^2 for sled team 1
    1.18 m/s^2 for sled team 2
51. (a) 0.5 m/s^2
    (b) 8.3 m/s^2

Unit 2 Self Quiz, pp. 206–207

1. (a)
2. (a)
3. (a)
4. (b)
5. (a)
6. (c)
7. (b)
8. (c)
9. (c)
10. (d)
11. (c)
12. (c)
13. (b)
14. (c)
15. (c)
16. (c)
17. F
18. F
19. F
20. T
21. F
22. F
23. T
24. T
25. F
26. T
27. F
28. T
29. F
30. F
31. F
32. T
33. T
34. F
35. T
36. F

Unit 2 Review, pp. 208–215

1. (b)
2. (a)
3. (a)
4. (b)
5. (a)
6. (a)
7. (b)
8. (d)
9. (c)
10. (a)
11. (c)
12. (a)
13. (a)
14. F
15. F
16. F
17. T
18. F
19. F
20. T
21. F
22. F
23. T
24. T
25. (a) iv
    (b) ii
    (c) vi
    (d) v
    (e) i
    (f) iii
31. 40 800 N [northward]
34. 78 N [left]
36. (a) 160 N [forward]
    (b) 4.2 N [down]
37. (a) 2.0 m/s^2 [N]
    (b) 3.44 m/s^2 [up]
38. 0.23 N [opposite direction of motion]
39. 5.5×10^4 m/s^2 [S]
40. (a) 3.3 m/s^2 [right]
    (b) 3.1 m/s^2 [right]
    (c) 1.3 N
42. (a) 0.48 m/s^2
43. (a) 4.9 N
    (b) 5.3 N
    (c) 4.4 N
44. (d) 2.2 N
45. (b) 9.79 N/kg
48. 22 N [down]
49. (c) 2100 N [up]
50. (a) 0.61
51. (a) 5.2 N
    (b) 1.6 N
52. (a) 0.40
    (b) 0.29
53. 7.7 m/s^2 [forward]
54. 18 N
55. 3.1 m
60. 17 N
61. 84 N
62. (a) 0.50 m/s^2 [forward]
63. 0.03 m/s^2 [left]
64. (a) 4.2 N
    (b) 420 N
65. (a) 3.7 m/s^2
    (b) 670 N
    (c) 3200 N
66. (b) 2.2 m/s^2 [right] for the jumpers
    1.3 m/s^2 [left] for the boat
68. (a) 2.0 m/s^2 [forward]; 8.0 N
    (b) 1.0 m/s^2 [forward]; 8.0 N
69. (a) 2.6 m/s^2 [forward]
    (b) 11 N for rope A
    25 N for rope B
70. (a) 250 N [up] for box 1
    690 N [up] for box 2
    (b) 190 N [up] for box 1
    630 N [up] for box 2
    (c) 250 N [up] for box 1
    630 N [up] for box 2
71. 4.4 m/s^2
72. (a) 50 kg
    (b) 0.49
73. 0.56 m/s^2 for team 1
    0.60 m/s^2 for team 2
74. (a) 7.8 m/s^2
    (b) 0.74 m/s^2

Unit 3

Are You Ready?, pp. 218–219

1. (a) 12 m
   (b) 0 N

5.1 Questions, p. 229

1. 325 J
2. (a) 18 kJ
   (b) −9.7 kJ
   (c) 0 J
   (d) 0 J
3. (a) 830 J
   (b) 420 J
4. (b) 21 N
   (c) −250 J
5. (b) 12 kJ
   (c) −12 kJ
6. 2 J
7. (a) 9.9 m
   (b) The work done by gravity is −190 J. The work done by the rope is 240 J.
   (c) 44 J
   (d) 4.4 N; 44 J
9. (a) The work done in section A is 10 J; section B is 2.5 J; section C is −2.5 J.
   (b) 10 J

5.2 Questions, p. 235

1. 11 m/s
2. (a) 39 J
   (b) 32 N
3. (a) 6.6 kJ
   (b) 11 m
   (c) 4.1 m
   (d) 0 J
4. 240 J

5.3 Questions, p. 241

2. (a) 13 J
   (b) 21 m
   (c) 24 m/s
3. 21 m

5.4 Questions, p. 249

1. 3800 J
2. (a) 42 %
3. 24 m/s

5.5 Questions, p. 254

1. (a) 5400 J
   (b) 170 W
2. (a) 3.6 s; 890 W
4. (a) 27 kWh
   (b) $540

Chapter 5 Self-Quiz, p. 261

1. (b)
2. (c)
3. (b)
4. (b)
5. (a)
6. (b)
7. (b)
8. (b)
9. F
10. T
11. T
12. F
13. F
14. F
15. F

Chapter 5 Review, pp. 262–267

1. (d)
2. (c)
3. (a)
4. (b)
5. (c)
6. F
7. T
8. F
9. F
10. (a) iii
   (b) iv
   (c) ii
   (d) i
12. no work done
14. 48 000 J
26. 110 kJ
29. −380 kJ
30. 210 kJ
31. 63 m
34. 48 m/s
37. 23 m/s [down]
38. (a) 1480 J
   (b) 1230 J
39. 68 MJ
42. 360 W
43. 360 W
44. 2.0×10^4 N; 1.4×10^5 m/s^2
47. (a) 220 J
   (b) −220 J
   (c) 0 J
48. 3.0×10^2 N when lifted
   1.5×10^3 N when falling
49. (a) 110 J
   (b) 110 J
   (c) 21 m/s
50. (a) 5.8×10^6 J
   (b) 1.6 MJ at the beginning
   3.7 MJ at the end
   (c) 2.1 MJ
53. (a) 86 N
   (b) 1900 J
   (c) 87 %
57. 95 J
59. (a) 0.2¢
63. (a) 7.7 m
   (b) 6.0×10^4 J
   (c) 54 kW
64. 7.9 m/s

6.3 Questions, p. 287

2. 1.8×10^2 J
3. 1.0×10^4 J
4. copper
5. 18 °C
6. 220 g
7. 4.1×10^2 J/kg•°C
8. 36.8 °C

6.4 Questions, p. 295

2. (c) melting point is 55 °C
   boiling point is 90 °C
6. 2.6×10^6 J
7. 3.2×10^5 J
8. 2.7×10^6 J

Chapter 6 Self-Quiz, p. 309

1. (a)
2. (b)
3. (d)
4. (b)
5. (a)
6. (d)
7. (c)
8. (c)
9. (d)
10. F
11. F
12. T
13. F
14. F
15. T
16. T
17. T
18. T
19. F

Chapter 6 Review, pp. 310–315

1. (d)
2. (b)
3. (d)
4. (b)
5. (c)
6. (a)
7. (a)
8. (d)
9. F
10. T
11. F
12. T
13. F
14. T
15. T
16. (a) ii
   (b) iii
   (c) i
   (d) iv
18. $Q = mc\Delta T$
33. -1.8×10^4 J
34. 160 °C
35. 3.5 kg
40. 2.4×10^5 J
41. glass
44. 0.84 kg
45. 88 mL
63. (a) 5.3×10^5 J
66. specific heat capacity is
   2.40×10^2 J/kg•°C; silver
67. 0.10 kg

7.3 Questions, p. 333

2. (b) (i) 77 %
   (ii) 15 %
3. (a) 47 g
   (b) 26 g
5. approximately 2950 years ago
7. about 3.6 million years

7.4 Questions, p. 341

1. (a) 8.2×10^{-14} J
   (b) 1.5×10^{-10} J
2. 5.0 g
3. 5.8×10^{-14} J
4. 2.5×10^{-11} J

7.5 Questions, p. 347

3. (a) 7.54 MeV
   (b) 13.0 u
4. (a) 3.52 MeV/nucleon in
   Sample Problem 1
   0.749 MeV/nucleon in
   Sample Problem 2

Chapter 7 Self-Quiz, p. 353

1. (c)
2. (a)
3. (b)
4. (c)
5. (d)
6. (b)
7. (a)
8. (b)
9. (a)
10. F
11. T
12. F
13. F
14. T
15. F
16. T
17. F

Chapter 7 Review, pp. 354–359

1. (c)
2. (b)
3. (d)
4. (a)
5. (c)
6. (a)
7. (a)
8. (c)
9. (d)
10. (b)
11. F
12. T
13. T
14. T
15. T
16. T
17. T
18. F
19. F
20. (a) iii
   (b) i
   (c) iv
   (d) v
   (e) ii
   (f) vi
25. (a) atomic number 4
   2 electron shells
   (b) atomic number 29
   4 electron shells
   (c) atomic number 18
   3 electron shells
26. (a) 19 protons
   (b) 19 electrons
   (c) 24 neutrons
36. (a) 110 mg
   (b) 448 mg
37. (a) 0.062 445 u; 58.1 MeV
   (b) 0.132 52 u; 123 MeV
45. (b) radium
   ${}^{232}_{90}\text{Th} \rightarrow {}^{228}_{88}\text{Ra} + {}^{4}_{2}\text{He}$
47. (b) 140 MeV
48. 26 MeV

Unit 3 Self-Quiz, pp. 362–363

1. (c)
2. (a)
3. (d)
4. (c)
5. (b)
6. (c)
7. (a)
8. (d)
9. (c)
10. (a)
11. (b)
12. (c)
13. (d)
14. (b)
15. (a)
16. (d)
17. (b)
18. F
19. F
20. T
21. T
22. T
23. F
24. T
25. F
26. T
27. F
28. F
29. T
30. T
31. F
32. F
33. T
34. F
35. T
36. F

Unit 3 Review, pp. 364–371

1. (c)
2. (c)
3. (a)
4. (b)
5. (d)
6. (d)
7. (a)
8. (b)
9. (c)
10. (b)
11. (b)
12. (a)
13. (d)
14. (b)
15. (c)
16. (d)
17. (c)
18. (b)
19. T
20. F
21. F
22. F
23. T
24. F
25. F
26. T
27. T
28. F
29. T
30. T
31. F
32. F
33. (a) iv
   (b) iii
   (c) v
   (d) ii
   (e) i
34. (a) 0 J
   (b) −0.083 J
36. 32 m/s
39. (a) 44 J
   (b) 66 J
   (c) 24 m/s
40. 44 m/s
42. (a) 0.68 J
   (b) 0.39 J
   (d) 57 %
44. 1.6 %
45. 88 W
46. 41 %
47. 45 kJ
49. (a) 253 K
   (b) −205 °C
50. 1 °C = 1.8 °F
54. 1.19×10^2 J/kg•°C
55. 1.1×10^2 J
56. 84.6 J
57. 106 g
58. 6800 J
66. 0.528 u; -7.90×10^{-11} J
67. 22.2 %
71. 4.3×10^{-12} J, or 26 MeV
73. (b) 2600 J
   (c) −2600 J
74. 69.3 J
75. 20 000 J
77. (a) 200 J
   (b) 200 J
   (c) 4 m
80. 86 %
81. 37 kW
82. (a) 5.6×10^8 J
   (b) 9.3×10^7 W
83. 111 W
90. 43 kJ
92. 8800 J
93. 54.6 kJ to solidify and cool the lead; 2630 kJ to heat and boil the water

96. (a) 1000 years
    (b) 0.8 g
97. 1.6 %
99. 17 days

Unit 4

Are You Ready?, pp. 374–375

7. 2.5 g/cm^3 or 2500 kg/m^3
20. (a) $c = \dfrac{da - a}{b - 1}$
    (b) $c = \dfrac{b^2 - a^4}{4a}$

8.4 Questions, p. 391

1. 0.53 m
2. 1000 m/s
3. 0.408 m
4. $t_{\text{p-wave}} = 5.0$ min
   $t_{\text{s-wave}} = 8.9$ min
7. 4

8.5 Questions, p. 397

3. 1000 km/h
9. 1000 : 1

Chapter 8 Self-Quiz, p. 407

1. (c)
2. (a)
3. (d)
4. (b)
5. (a)
6. (d)
7. (d)
8. (a)
9. (c)
10. (b)
11. F
12. T
13. F
14. T
15. T
16. F
17. T
18. F
19. F
20. T

Chapter 8 Review, pp. 408–413

1. (b)
2. (c)
3. (d)
4. (a)
5. (c)
6. (b)
7. (c)
8. (a)
9. (b)
10. (d)
11. (d)
12. (c)
13. (a)
14. (a) iv
    (b) ii
    (c) v
    (d) iii
    (e) i
24. 3.57 Hz
25. 0.012 s
26. 2.07 m/s
28. (a) 25 %
    (b) 75 %
    (c) 50 %
    (d) 0
29. 2.8 m/s
30. 78.0 cm
31. 0.113 kg/m
32. 0.27 kg
33. 31 m/s
34. 0.0625 kg/m
37. 340 m/s
38. 29.0 °C
40. 0.805
41. 519 km/h
48. 660 Hz
49. 0.031 kg
50. 16.6 N
51. 0.59 N
52. 1922 °C
53. 6.6 °C
54. 3200 km/h
60. (a) 41.8 m to 43.4 m

9.2 Questions, p. 426

5. 94 Hz
6. 290 Hz
7. 1.3 m

9.5 Questions, p. 435

3. 320 Hz
4. 22 m/s
5. approaching = 480 Hz
   passing = 440 Hz
6. 58 m/s

Chapter 9 Self-Quiz, p. 441

1. (d)
2. (b)
3. (b)
4. (d)
5. (c)
6. (b)
7. (a)
8. (c)
9. F
10. F
11. T
12. T
13. F
14. T
15. F
16. F
17. T

Chapter 9 Review, pp. 442–447

1. (b)
2. (c)
3. (b)
4. (d)
5. (b)
6. (d)
7. (d)
8. (b)
9. (a)
10. (c)
11. (a)
12. (c)
13. (b)
14. (b)
15. (d)
16. F
17. F
18. T
19. T
20. F
21. F
22. F
23. F
24. T
25. T
26. T
27. F
28. F
29. T
30. T
31. (a) iii
    (b) iv
    (c) v
    (d) i
    (e) ii
32. (a) fixed
    (b) free
    (c) free
    (d) fixed
38. (a) $f_1 = 142$ Hz
        $f_2 = 426$ Hz
        $f_3 = 709$ Hz
    (b) $f_1 = 146$ Hz
        $f_2 = 437$ Hz
        $f_3 = 728$ Hz
39. 0.97 m
48. 3.2 Hz; 6.4 Hz; 9.6 Hz
49. 0.92 m or 30.6 cm
51. (a) 146 Hz
    (b) 1.17 m
57. 16.5 Hz

10.2 Questions, p. 460

4. 170 Hz
5. (a) 1.2 m
   (b) 240 Hz, 360 Hz
8. (i) 215 Hz
   (ii) 211 Hz
9. (a) 0.41 m
   (b) 0.21 m
10. (a) 92.0 cm; 120 cm; 152 cm
    (b) 372 Hz; 285 Hz; 225 Hz

10.3 Questions, p. 463

1. 22 dB
2. 2.0 s

10.7 Questions, p. 474

2. max: 0.3 s; min: 7 ms
3. (b) 3.1 mm

Chapter 10 Self-Quiz, p. 479

1. (b)
2. (c)
3. (c)
4. (b)
5. (a)
6. (d)
7. (d)
8. (c)
9. (a)
10. F
11. T
12. T
13. F
14. F
15. F
16. F
17. F
18. F
19. T
20. F

Chapter 10 Review, pp. 480–485

1. (d)
2. (c)
3. (c)
4. (a)
5. (c)
6. (d)
7. (d)
8. (a)
9. (b)
10. F
11. T
12. F
13. F
14. (a) ii
    (b) iii
    (c) i
15. 1000 Hz to 5500 Hz
35. 2.50 m
36. (a) 0.328 m
    (b) 335 Hz
37. 0.750 m
38. (a) 147 Hz
    (b) 1.30 m
55. 3.0 kHz
57. (a) 221 Hz
59. (a) $f = \dfrac{\sqrt{\dfrac{F_T}{\mu}}}{2L}$
    (b) $F_T = 4f^2Lm$
    (c) 0.24 m
    (d) 0.19 m
    (e) 8.6×10^{-4} kg

Unit 4 Self-Quiz, pp. 488–489

1. (c)
2. (b)
3. (b)
4. (a)
5. (a)
6. (a)
7. (d)
8. (b)
9. (d)
10. (d)
11. (d)
12. (c)
13. (c)
14. (b)
15. T
16. T
17. F
18. T
19. T
20. F
21. T
22. T
23. F
24. T
25. F
26. T
27. F
28. T
29. F
30. T
31. F
32. F
33. T
34. F
35. T
36. F
37. F
38. T
39. F

Unit 4 Review, pp. 490–497

1. (c)
2. (a)
3. (c)
4. (b)
5. (a)
6. (d)
7. (a)
8. (a)
9. (a)
10. (c)
11. (a)
12. (b)
13. (d)
14. (b)
15. (d)
16. (c)
17. (d)
18. (b)
19. (b)
20. (d)
21. (b)
22. (a)
23. (c)
24. F
25. F
26. T
27. F
28. T
29. T
30. T
31. F
32. T
33. F
34. F
35. F
36. T
37. (a) iv
    (b) ii
    (c) i
    (d) v
    (e) iii
    (f) x
    (g) viii

    (h) ix
    (i) vii
    (j) vi
38. 1.94 m
39. 17 m
45. 0.06 kg/m
46. 0.80 m/s
47. 340 m
49. 90 Hz
51. $\frac{1}{2}$ wavelength
52. 30 cm
56. 2.5 cm
61. 13 dB
64. $\frac{1}{4}$ wavelength
68. (a) 130 m/s
    (b) 0.0011 kg/m
    (c) 18 N
98. (b) 1 : 5 or 3 : 2
    (c) $\frac{2}{3}\lambda$

Unit 5

Are You Ready? pp. 500–501

12. (b)
14. (a) series
15. (a) lamp
    (b) resistor
    (c) connecting wire
    (d) battery
    (e) open switch
18. (a) $V = IR$
    (b) $I = \frac{V}{R}$
19. (a) 5
    (b) $\frac{21}{10}$; 2.1

11.1 Questions, p. 507

2. 9600 W
3. 2.5 min
4. 1.5×10^8 J; 42 kWh
5. 1320 h; 1.8×10^9 J; 5.0×10^2 kWh

11.3 Questions, p. 513

1. 560 V
2. 1.1 J
3. 1.6 C
4. (a) 120 V
    (b) 3.3×10^{21} electrons
5. 0.18 C
7. (a) gain
    (b) drop
    (c) drop
    (d) gain
    (e) gain
    (f) drop

11.5 Questions, p. 518

2. 0.54 A
3. 5.8×10^4 C
4. 680 s; 11 min
5. 0.71 s
6. 3 h

11.7 Questions, p. 526

2. 56 Ω
3. 9×10^{-5} A
4. 0.1 A
5. 0.65 A
6. 16.7 V

11.8 Questions, p. 530

5. (a) 48.0 Ω
    (b) 12.0 Ω
    (c) 24.0 Ω
    (d) 36.0 Ω

11.9 Questions, p. 535

1. (a) I_{source} = 0.33 A; I_1 = 0.33 A;
    I_2 = 0.17 A; I_3 = 0.17 A
    V_1 = 4.0 V; V_2 = 2.0 V;
    V_3 = 2.0 V
    R_{source} = 18.0 Ω
    (b) I_{source} = 0.17 A; I_1 = 0.17 A;
    I_2 = 0.083 A; I_3 = 0.083 A;
    I_4 = 0.083 A; I_5 = 0.083 A;
    I_6 = 0.17 A
    V_1 = 2.0 V; V_2 = 1.0 V;
    V_3 = 1.0 V; V_4 = 1.0 V;
    V_5 = 1.0 V; V_6 = 2.0 V
    R_{source} = 36.0 Ω
    (c) I_{source} = 0.30 A;
    I_1 = 0.30 A;
    I_2 = 0.10 A; I_3 = 0.10 A;
    I_4 = 0.20 A
    V_1 = 3.6 V; V_2 = 1.2 V;
    V_3 = 1.2 V; V_4 = 2.4 V
    R_{source} = 20.0 Ω
    (d) I_{source} = 0.25 A; I_1 = 0.25 A;
    I_2 = 0.13 A; I_3 = 0.13 A;
    I_4 = 0.13 A; I_5 = 0.13 A
    V_1 = 3.0 V; V_2 = 1.5 V;
    V_3 = 1.5 V; V_4 = 1.5 V;
    V_5 = 1.5 V
    R_{source} = 24.0 Ω
2. V_1 = 6.0 V; V_3 = 5.0 V
    I_1 = 0.20 A; I_3 = 0.20 A;
    I_{source} = 0.20 A
    R_2 = 20 Ω; R_3 = 25 Ω;
    R_{total} = 75 Ω
3. V_1 = 1.5 V; V_2 = 1.5 V; V_3 = 1.5 V
    I_2 = 0.20 A; I_3 = 0.30 A;
    I_{source} = 0.60 A
    R_1 = 15 Ω; R_{total} = 2.5 Ω
4. V_{source} = 14.5 V; V_2 = 2.5 V;
    V_4 = 7.0 V; V_5 = 7.0 V;
    I_{source} = 0.50 A; I_1 = 0.20 A;
    I_5 = 0.40 A
    R_1 = 13 Ω; R_2 = 8.3 Ω; R_3 = 10 Ω;
    R_5 = 18 Ω; R_{total} = 29 Ω

Chapter 11 Self-Quiz, p. 539

1. (b)
2. (d)
3. (a)
4. (b)
5. (d)
6. (a)
7. (c)
8. (b)
9. F
10. T
11. F
12. F
13. T
14. T
15. T

Chapter 11 Review, pp. 540–545

1. (b)
2. (b)
3. (c)
4. (d)
5. (b)
6. (c)
7. (a)
8. (d)
9. (c)
10. T
11. F
12. T
13. F
14. F
15. T
16. T
17. F
18. F
19. $V_{\text{source}} = V_1 + V_2 + V_3$
20. $\frac{1}{R_{\text{parallel}}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$
22. 4200 MW
23. 0.18 kWh
24. 22 kWh; 78 MJ
25. 4 W
26. (a) 190 MW
    (b) 160 MJ
27. 9.0 V
28. 4.0 C
29. 2600 C
31. (a) 3.0×10^4 C
    (b) 3400 W
    (c) 14 A
33. 7.4 mA
34. 58 000 C
35. 4 s
38. (a) 6.0 V
    (b) 4.5 V
39. (a) 3.2 mA
    (b) 3.8 mA
40. 80 Ω
41. 68 mV
42. R_1 = 9.1 kΩ; R_2 = 15 kΩ
43. 8.7 Ω
44. 1.2 Ω
45. 15 Ω
46. R_1 = 19 Ω; V_2 = 11 V;
    I_2 = 0.37 A
47. I_1 = 4.0 A; I_2 = 170 mA;
    I_3 = 3.8 A; R_3 = 2.6 Ω
48. (a) 1600 MW
49. 220 MW
50. 15 h
51. $E_{\text{input}} = 4.3 \times 10^5$ J
    $E_{\text{output}} = 4.8 \times 10^4$ J
52. 360 h; 3.8 kWh
53. 4.76 C
54. (a) 17 Ω
    (b) 58 s
55. (a) 5.4 C
    (b) 6.1 C
56. (a) R_3 = 12 Ω; I_2 = 0.20 A
    (b) 29 s
62. (a) 0.67 A
    (b) 32 V
63. (a) $R_1 = R_2$ = 55 Ω
    (b) 0.073 A
64. (a) $R_4 = 2.50 \times 10^2$ Ω
    I_1 = 0.250 A
    I_2 = 0.150 A
    I_4 = 0.100 A
    (b) V_2 = 16.7 V
    V_3 = 8.30 V
65. (a) $R_1 = 2.0 \times 10^2$ Ω
    $R_2 = 1.6 \times 10^2$ Ω
    R_3 = 80 Ω
    $R_4 = 2.0 \times 10^2$ Ω
    (b) 110 mA

12.2 Questions, p. 556

5. east

Chapter 12 Self-Quiz, p. 579

1. (b)
2. (d)
3. (b)
4. (c)
5. (d)
6. (b)
7. (b)
8. (a)
9. (c)
10. (b)
11. F
12. T
13. F
14. F
15. T
16. T
17. F
18. T

Chapter 12 Review, pp. 580–585

1. (d)
2. (d)
3. (d)
4. (c)
5. (b)
6. (d)
7. (a) iii
    (b) i
    (c) iv
    (d) ii

13.4 Questions, p. 604

1. (a) 180° and 0°
    (b) 90° and 270°
3. 60 rotations per second

13.5 Questions, p. 609

7. 8.0 V; 4.5 A
9. 8 : 1

13.6 Questions, p. 612

2. (a) 20 %
    (b) 0.2 %
    (c) 45 %

Chapter 13 Self-Quiz, p. 615

1. (d)
2. (b)
3. (b)
4. (c)
5. (c)
6. (b)
7. (b)
8. F
9. F
10. T
11. F
12. T
13. T
14. F
15. T

Chapter 13 Review, pp. 616–621

1. (d)
2. (c)
3. (a)
4. (c)
5. (c)
6. (a)
7. (c)
8. (d)
9. (c)
10. F
11. T
12. T
13. F
14. F
15. T
16. T

17. F
18. coil A
19. 115 windings
26. step-up transformer
27. (a) more than 50 coils
    (b) less than 50 coils
28. (a) less than 100 coils
    (b) more than 100 coils
29. (a) 100 V
    (b) 2 : 1
30. (a) 450 V
    (b) 3 : 2
31. (a) 80 V
    (b) 7 A
32. (a) 30 V
    (b) 40 coils
33. (a) 290 coils
    (b) 12 A
34. $I = 7.5 \times 10^4$ A
35. 53 kV
36. 6.0 MW
37. (a) 480 MW
    (b) 1.2 MW
38. 16 %
39. 0.72 Ω
40. 2600 MW
45. 35 cm
50. (a) 30 coils
    (b) $I_p = 20$ A; $I_s = 80$ A
51. (a) 10.0 A
    (b) $V_s = 42$ V; $V_p = 14$ V
52. (a) 175 V
    (b) 4.0×10^2 Ω
53. (a) 1000 coils
    (b) 1.3 Ω
54. 0.25 %
55. 7.5 Ω
56. 850 MW
57. 400 windings
58. $I_s = 13$ kA; $V_s = 2.0 \times 10^2$ kV
59. 720 MW
60. $I_s = 1.9$ kA
    $V_s = 630$ kV
    $V_p = 130$ kV
    $I_p = 9.5$ kA
61. (c) $V_1 = 6.0$ V, $V_2 = 24$ V

Unit 5 Self-Quiz, pp. 624–625

1. (c)
2. (c)
3. (d)
4. (d)
5. (b)
6. (c)
7. (a)
8. (d)
9. (b)
10. (a)
11. (c)
12. (d)
13. (d)
14. (a)
15. (d)
16. (a)
17. (b)
18. F
19. F
20. T
21. T
22. F
23. T
24. F
25. F
26. T
27. F
28. F
29. T
30. T
31. T
32. T
33. F
34. T
35. F
36. F

Unit 5 Review pp. 626–633

1. (b)
2. (a)
3. (d)
4. (c)
5. (b)
6. (c)
7. (b)
8. (c)
9. (b)
10. (a)
11. (c)
12. (b)
13. (d)
14. (b)
15. (c)
16. F
17. F
18. T
19. T
20. T
21. F
22. T
23. F
24. T
25. T
26. F
27. T
28. (a) v
    (b) viii
    (c) i
    (d) ii
    (e) iii
    (f) ix
    (g) vii
    (h) iv
    (i) vi
29. 4500 MW
30. 28 MJ
31. 3.3 W
32. 4.5 C
33. 7.2 mA
34. 8.0 s
36. (a) 6.4 mA
    (b) 4.2 mA
37. 650 mV
38. 15 Ω
42. (a) into the page
    (b) counter-clockwise
    (c) out of the page
46. into the page
53. coil A
56. 150 coils
57. step-down transformer
58. 36 kA
59. 6.3 MW
60. 3.6 MW
61. 0.50 Ω
62. 3300 MW
63. 450 MW
64. 56 s
66. 5.5 C
67. (a) 7.1 C
    (b) 5.3 C
68. (a) $R_3 = 16$ Ω; $I_2 = 0.20$ A
    (b) 21 s
72. (a) $R_1 = R_2 = 91$ Ω
    (b) $I_3 = 36$ mA
81. 16 cm
84. (a) 120 V
    (b) 2 : 1
85. (a) 128 V
    (b) 16.0 A
86. (a) 30 coils
    (b) $I_p = 3.0 \times 10^1$ A,
        $I_s = 150$ A
87. (a) 1800 coils
    (b) 0.83 Ω
88. 15 Ω
89. 690 MW
90. 1300 MW

Glossary

A

acceleration ($\vec{a}_{\text{av}}$) how quickly an object's velocity changes over time (rate of change of velocity)

acceleration–time graph a graph describing motion of an object, with acceleration on the vertical axis and time on the horizontal axis

acceleration due to gravity (g) the acceleration that occurs when an object is allowed to fall freely; close to Earth's surface, g has a value of 9.8 m/s^2

aeroelastic flutter the response when the energy added to a structure vibrating in air exceeds the energy lost due to damping, causing large vibrations

alpha (α) decay nuclear reaction in which an alpha particle is emitted

alpha particle a particle emitted during alpha decay composed of a helium nucleus containing two protons and two neutrons

alternating current an electric current that periodically reverses direction

ammeter electrical device that measures electric current; must be connected to the circuit in series

amplitude the maximum displacement of a wave from its equilibium point

antinode in a standing wave, the location where the particles of the medium are moving with greatest speed; the amplitude will be twice the amplitude of the original wave

applied force ($\vec{F}_{\text{a}}$) a force that results when one object makes contact with another and pushes or pulls on it

atomic number the number of protons in the nucleus

atomic mass unit (u) a unit of mass equal to 1.66×10^{-27} kg

audible sound wave sound wave in the range of human hearing, 20 Hz to 20 kHz

average speed (v_{av}) the total distance travelled divided by the total time taken to travel that distance

average velocity ($\vec{v}_{\text{av}}$) the total displacement, or change in position, divided by the total time for that displacement

B

beat periodic change in sound intensity caused by the interference between two nearly identical sound waves

beat frequency the frequency of beats produced by the interference of two waves with slightly different frequencies; equal to the difference in the frequencies of the interfering waves

beta (β) decay nuclear reaction in which a beta particle is emitted or captured

beta particle a high-energy electron or positron ejected or captured by a nucleus during beta decay

binding energy the energy used to hold a nucleus together

boiling point the temperature at which a liquid changes into a gas; equal to the condensation point for a given substance

brownout reduced supply of electricity caused by system damage or excess demand

building acoustics the total effect of sound produced in an enclosed or restricted space

C

Celsius scale the temperature scale based on the boiling point and freezing point of water

chain reaction the repeated series of reactions in which the products of one reaction generate subsequent reactions

coefficient of friction (μ) the ratio of the force of friction to the normal force

coefficient of kinetic friction (μ_{K}) the ratio of kinetic friction to the normal force

coefficient of static friction (μ_{S}) the ratio of the maximum force of static friction to the normal force

component vectors vectors which when added together give the original vector from which they were derived; one component is parallel to the x-axis and the other is parallel to the y-axis

compression the region in a longitudinal wave in which the medium's particles are closer together

condensation point the temperature at which a gas changes into a liquid; equal to the boiling point for a given substance

constructive interference the process of forming a wave with a larger amplitude when two or more waves combine

convection the transfer of thermal energy through a fluid that occurs when colder, denser fluid falls and pushes up warmer, less dense fluid

convection current a current that occurs when a fluid is continuously heated; caused by warmer, less dense fluid being constantly pushed upward as colder, denser fluid falls downward

cooling graph a graph that shows the temperature changes that occur while thermal energy is being removed from a substance

crest the maximum point of a transverse wave

D

damping a reduction in the amplitude of a wave as a result of energy absorption or destructive interference

daughter atom the product atom in a nuclear reaction

decibel (dB) the unit of sound level used to describe sound intensity level

destructive interference the process of forming a wave with a smaller amplitude when two or more waves combine

direct current (DC) the movement of electrons in only one direction

directed line segment a straight line between two points with a specific direction

direction the line an object moves along from a particular starting point

displacement ($\Delta\vec{d}$) the change in position of an object

distance (d) the total length of the path travelled by an object in motion

Doppler effect when a source of sound approaches an observer, the observed frequency of the sound increases; when the source moves away from an observer, the observed frequency of the sound decreases

dynamics the study of the causes of motion

E

echo the sound energy reflected off a surface back to the producer of sound

echolocation the location of objects through the analysis of echoes, or reflected sound

efficiency the amount of useful energy produced in an energy transformation expressed as a percentage of the total amount of energy used

elastic the property of a medium that returns to its original shape after being disturbed

electric generator a device that transforms other forms of energy into electrical energy

electrical heating system a system that uses electricity to produce thermal energy for heating

electric potential the amount of electric potential energy associated with charges

electric potential difference (V) the change in electric potential energy associated with charges at two different points in a circuit

electrical power (P) the rate of transformation of electrical energy

electrical power grid a large electricity distribution system composed of a network of electrical power plants and electricity distribution towers and cables

electrical resistance (R) a property of matter that describes how difficult it is for electric current to travel through a material

electromagnet any device that produces a magnetic field as a result of an electric current

electromagnetic induction the production of electric current in a conductor moving through a magnetic field

electron a negatively charged particle found in the space surrounding the nucleus of an atom

electrostatic force the force of attraction or repulsion due to electric charges

energy the capacity to do work

energy resource energy-rich substance

energy transformation the change of one type of energy into another

equivalent resistance the total resistance of a group of resistors connected in series or parallel

excited state state in which one or more electrons are at higher energy levels than in the ground state

F

Fahrenheit scale the temperature scale based on the boiling point and freezing point of brine

first law of motion an object will remain at rest or continue to move at constant velocity when the net force on the object is zero

fixed-end reflection a reflection that occurs at a media boundary where one end of the medium is unable to vibrate; reflections are inverted

force field a region of space surrounding an object that can exert a force on other objects that are placed within that region and are able to interact with that force

force of gravity ($\vec{F}_g$) force of attraction between any two objects

forced-air heating system a system that moves hot air to heat a building

fossil fuel fuel produced by the decayed and compressed remains of plants that lived hundreds of millions of years ago

free-body diagram (FBD) a simple drawing of an object showing all the forces that are acting on it

free-end reflection a reflection that occurs at a media boundary where the second medium is less dense than the first medium; reflections have an amplitude with the same orientation as the original wave

free fall the motion of a falling object where the only force acting on the object is gravity

freezing point the temperature at which a liquid changes into a solid; equal to the melting point for a given substance

frequency (f) the number of complete cycles that occur in unit time, usually 1 s; measured in hertz (Hz)

friction ($\vec{F}_f$) opposes the sliding of two surfaces across one another; friction acts opposite to the motion or attempted motion

fundamental frequency or first harmonic (f_0) the lowest frequency that can produce a standing wave in a given medium

fusion the process by which a solid changes to a liquid

G

gamma (γ) decay a reaction in which an excited nucleus returns to a lower, more stable energy state, releasing a very high-energy gamma ray in the process

geothermal system a system that transfers thermal energy from under Earth's surface into a building to heat it, and transfers thermal energy from the building into the ground to cool the building

gravitational field strength the force per unit mass acting on an object when placed in a gravitational field

gravitational potential energy energy possessed by an object due to its position relative to the surface of Earth

ground state state in which all electrons are at their lowest possible energy levels

H

half-life the average length of time it takes radioactive material to decay to half of its original mass

harmonics whole-number multiples of the fundamental frequency

heat the transfer of thermal energy from a substance with a higher temperature to a substance with a lower temperature

heating graph a graph that shows the temperature changes that occur while thermal energy is absorbed by a substance

hot water heating system a system that uses hot water to heat a building

hydroelectricity electricity produced by transforming the kinetic energy of rushing water into electrical energy

I

in phase the state of two identical waves that have the same phase shift

inertia the property of matter that causes it to resist changes in motion; inertia is directly proportional to the mass of the object

infrasonic wave sound wave with a frequency below 20 Hz

instantaneous velocity ($\vec{v}_{inst}$) the velocity of an object at a specific instant in time

interference the process of generating a new wave when two or more waves meet

isotope a form of an element that has the same atomic number, but a different mass number than all other forms of that element

K

Kelvin scale the temperature scale developed using absolute zero as the point at which there is virtually no motion in the particles of a substance

kilowatt hour (kWh) measure of electrical energy

kinematics the study of motion

kinetic energy (E_K) energy possessed by moving objects

kinetic friction ($\vec{F}_K$) the force exerted on a moving object by a surface opposite to the direction of motion of the object

kinetic molecular theory the theory that describes the motion of molecules or atoms in a substance in terms of kinetic energy

Kirchhoff's current law (KCL) in a closed circuit, the amount of current entering a junction is equal to the amount of current exiting a junction

Kirchhoff's voltage law (KVL) in any complete path in an electric circuit, the total electric potential increase at the source(s) is equal to the total electric potential decrease throughout the rest of the circuit

L

latent heat (Q) the total thermal energy absorbed or released when a substance changes state; measured in joules

latent heat of fusion the amount of thermal energy required to change a solid into a liquid or a liquid into a solid

latent heat of vaporization the amount of thermal energy required to change a liquid into a gas or a gas into a liquid

law of conservation of energy energy is neither created nor destroyed; when energy is transformed from one form into another, no energy is lost

law of electromagnetic induction a change in the magnetic field in the region of a conductor induces a voltage in the conductor, causing an induced electric current in the conductor

Lenz's law if a changing magnetic field induces a current in a coil, the electric current is in such a direction that its own magnetic field opposes the change that produced it

linear density (μ) the mass per unit distance of a string; units are kilograms per metre (kg/m)

longitudinal wave a wave in which particles vibrate parallel to the direction of the flow of energy

M

Mach number (M) the ratio of the airspeed of an object to the local speed of sound

magnetic field a region of space around a magnet that causes a magnetic force on magnetic objects

mass defect the difference between the calculated mass of an atom, based on the nucleons and electrons present and the actual atomic mass

mass number the number of protons and neutrons in the nucleus

mechanical energy the sum of kinetic energy and gravitational potential energy

mechanical wave the transfer of energy through a material due to vibration

mechanical work (W) applying a force on an object that displaces the object in the direction of the force or a component of the force

mechanical resonance the transfer of energy from one object to another, causing large-amplitude vibrations when the second object has the same resonant frequency as the first

media boundary the location where two or more media meet

medium the material that permits the transmission of energy through vibrations

mega-electron volt (MeV) the energy required to accelerate an electron through a potential difference of 1 million volts

melting point the temperature at which a solid changes into a liquid; equal to the freezing point for a given substance

motion a change in an object's location as measured by a particular observer

motion with non-uniform velocity (accelerated motion) motion in which the object's speed changes or the object does not travel in a straight line

motion with uniform acceleration motion in which velocity changes at a constant rate

motion with uniform or constant velocity motion of an object at a constant speed in a straight line

motor principle a current-carrying conductor that cuts across external magnetic field lines experiences a force perpendicular to both the magnetic field and the direction of the electric current

music sound that originates from a combination of musical notes that originate from a source that vibrates in a uniform manner with one or more constant frequencies

N

net force ($\vec{F}_{\text{net}}$) the sum of all forces acting on an object

net motion the displacement of a particle over a certain time interval; the difference between the particle's initial and final positions

neutron an uncharged particle in the nucleus of an atom

newton (N) the SI unit of force ($1\ \text{N} = 1\ \text{kg} \cdot \text{m/s}^2$)

node in a standing wave, the location where the particles of the medium are at rest

noise sound that originates from a source that vibrates in a random manner

non-renewable energy resource a substance that cannot be replenished as it is used in energy-transforming processes

normal force ($\vec{F}_\text{N}$) a perpendicular force exerted by a surface on an object in contact with the surface; the normal force always points away from the surface

nuclear energy potential energy of protons and neutrons in atomic nuclei

nuclear fission the decomposition of large, unstable nuclei into smaller, more stable nuclei

nuclear fusion a nuclear reaction in which the nuclei of two atoms fuse together to form a larger nucleus

nuclear reaction the process by which the nucleus of an atom sometimes changes

nucleons particles in the nucleus of an atom; protons and neutrons

O

Ohm's law the potential difference between any two points in a conductor varies directly with the current between two points if the temperature remains constant

ohmmeter a device that measures electrical resistance

Oersted's principle whenever a charge moves through a straight conductor, a circular magnetic field is created around the conductor

out of phase the state of two identical waves that have different phase shifts

overtone a sound resulting from a string that vibrates with more than one frequency

P

parent atom the reactant atom in a nuclear reaction

passive solar design building design that uses the Sun's radiant energy directly for heating

period (T) the time for a vibrating particle to complete one cycle

phase in a continuous transverse or longitudinal wave, the x-coordinate of a unique point of the wave

phase shift a shift of an entire wave along the x-axis with respect to an otherwise identical wave

photon a high-energy particle with no mass

photovoltaic cell a device that transforms radiant energy into electrical energy

pitch the general perception of the highness or lowness of a sound; depends on the frequency, complexity, and loudness of the sound

position ($\vec{d}$) the distance and direction of an object from a reference point

position–time graph a graph describing the motion of an object, with position on the vertical axis and time on the horizontal axis

positron a particle with a positive charge and the same mass as an electron

potential energy a form of energy an object possesses because of its position in relation to forces in its environment

power (P) the rate of transforming energy or doing work

pressure (p) the force per unit area

principle of superposition at any point the amplitude of two interfering waves is the sum of the amplitudes of the individual waves

principle of thermal energy exchange when thermal energy is transferred from a warmer object to a colder object, the amount of thermal energy released by the warmer object is equal to the amount of thermal energy absorbed by the colder object

projectile an object that moves along a two-dimensional curved trajectory in response to gravity

projectile motion the motion of a projectile under gravity

proton a positively charged particle in the nucleus of an atom

Q

quality the pleasantness of a sound; related to the waveform of the sound

quantity of heat (Q) the amount of thermal energy transferred from one object to another

R

radiation the movement of thermal energy as electromagnetic waves; energy released when the nucleus of an unstable isotope undergoes a change in structure

radioisotope an unstable isotope that spontaneously changes its nuclear structure and releases energy in the form of radiation

radioactive decay the process by which a radioactive atom's nucleus breaks apart and forms different atoms

radioactivity a process by which the nucleus of an atom spontaneously disintegrates

range the horizontal distance travelled by a projectile

rarefaction the region in a longitudinal wave in which the medium's particles are farther apart

reference level a designated level to which objects may fall; considered to have a gravitational potential energy value of 0 J

renewable energy resource a substance with an unlimited supply or a supply that can be replenished as the substance is used in energy-transforming processes

resistor an electrical device that has a specific resistance value

resonance the condition in which the frequency of a wave equals the resonant frequency of the wave's medium

resonant frequency the frequency at which a medium vibrates most easily

resonator an object, usually a hollow chamber called a case box or a sounding board, that vibrates in resonance with the source of sound

resultant vector a vector that results from adding two or more given vectors

reverberation time the time required for the loudness of the sound to drop by 60 dB or until the sound is inaudible

right-hand rule for a solenoid the fingers of your right hand wrap around the coil in the direction of the conventional current, while your right thumb points in the direction of the north magnetic pole of the coil

right-hand rule for a straight conductor if you hold a straight conductor in your right hand with your right thumb pointing in the direction of the conventional current, your curled fingers will point in the direction of the magnetic field lines

right-hand rule for the motor principle if the fingers of your open right hand point in the direction of the external magnetic field and your thumb points in the direction of the conventional current, then your palm faces in the direction of the force on the conductor

rise vertical change between two points on a line

run horizontal change between two points on a line

S

second law of motion an object will accelerate in the direction of the net force; the magnitude of the acceleration is directly proportional to the magnitude of the net force and inversely proportional to the object's mass

seismic waves waves of energy that travel through Earth

scalar a quantity that has only magnitude (size)

simple harmonic motion any motion that repeats itself at regular intervals

slope (m) a measure of the steepness of a line

solar energy radiant energy from the Sun

solenoid a coiled conductor

sound a form of energy produced by rapidly vibrating objects detectable by sensory organs such as the ear

sound intensity the amount of sound energy being transferred per unit area; units are W/m^2

specific heat capacity (c) the amount of energy, in joules, required to increase the temperature of 1 kg of a substance by 1 °C; units are J/(kg•°C)

specific latent heat (L) the amount of thermal energy required for 1 kg of a substance to change from one state into another; measured in joules per kilogram (J/kg)

specific latent heat of fusion (L_f) the amount of thermal energy required to melt or freeze 1 kg of a substance; measured in joules per kilogram (J/kg)

specific latent heat of vaporization (L_V) the amount of thermal energy required to evaporate or condense 1 kg of a substance; measured in joules per kilogram (J/kg)

standing wave an interference pattern produced when incoming and reflected waves interfere with each other; the effect is a wave pattern that appears to be stationary

static friction ($\vec{F}_S$) a force of friction that prevents the sliding of two surfaces relative to one another

step-down transformer a transformer with fewer secondary windings than primary windings

step-up transformer a transformer with more secondary windings than primary windings

strong nuclear force the very strong force of attraction between nucleons

sympathetic vibration the response to a vibration with the same resonant frequency

system diagram a simple sketch of all objects involved in a situation

T

temperature a measure of the average kinetic energy of the particles in a substance

tension ($\vec{F}_T$) a pulling force from a rope or string on an object that always points toward the rope or string

terminal speed the maximum constant speed of a falling object

terminal velocity the velocity of an object when the force due to air resistance equals the force due to gravity on the object

thermal conduction the transfer of thermal energy that occurs when warmer objects are in physical contact with colder objects

thermal conductor a material that is a good conductor of thermal energy

thermal contraction the contraction of a substance as it cools down

thermal energy the total quantity of kinetic and potential energy possessed by the atoms or molecules of a substance

thermal expansion the expansion of a substance as it warms up

thermal insulator a material that is a poor conductor of thermal energy

third law of motion each action force has a reaction force that is equal in magnitude and opposite in direction

time of flight the time taken for a projectile to complete its motion

transformer an electromagnetic device that can raise or lower voltage

translational molecular motion the straight-line motion of a molecule; this motion is typical of gases because the particles in liquids and solids are not free to move in this manner

transmission the motion of a wave through a medium, or motion of a wave from one medium to another medium

transmutation a nuclear decay process in which daughter atoms are different elements from parent atoms

transverse wave a wave in which particles vibrate perpendicular to the direction of the flow of energy

trough the minimum point of a transverse wave

tsunami an enormous sea wave or a series of enormous sea waves caused by an earthquake or other disturbance

U

ultrasonic wave sound wave with a frequency above 20 kHz

universal wave equation $v = f\lambda$

V

vector a quantity that has magnitude (size) and direction

vector scale diagram a vector diagram drawn using a specific scale

velocity–time graph a graph describing the motion of an object, with velocity on the vertical axis and time on the horizontal axis

vibration the cyclical motion of an object about an equilibrium point

voltmeter electrical device that measures electric potential difference

W

wave speed (v) the rate at which a wave is travelling through a medium; also a measure of how fast the energy in the wave is moving

waveform the shape of a wave when graphed

wavelength (λ) the distance between two similar points in successive identical cycles in a wave, such as from crest to crest or trough to trough

work–energy principle the net amount of mechanical work done on an object equals the object's change in kinetic energy

Index

A

Absolute zero, 272
Absorption coefficients, 461
Accelerated motion, 18
  motion with uniform acceleration, 27, 36–39
Acceleration, 21
  average, 23
  determining from velocity-time graph, 22–24
  due to gravity, 40, 191–92
  of falling objects, 83, 134–35
  near Earth's surface, 40–43
  second law of motion applied, 132–33
  solving for final velocity, 25
  uniform vertical, 40
Acceleration-time graphs, 31–32
  relationships among linear motion graphs, 32–34
Accelerometers, 84–85
Acoustical beats, 427
Acoustics, 461–63, 477
Action-at-a-distance forces, 116
Action forces, 137–41
Action-reaction law, 137. *See also* Newton's third law of motion
Adapter, AC to DC, 597
Aeroelastic flutter, 464, 470
Airbags, 182
Aircraft
  breaking the sound barrier, 398–99
  vibrations in, 469–71
Air resistance
  and free fall, 162–63
  as type of friction, 169
Algebra equations, 652–53
Algebraic approach to motion in two dimensions, 66–74, 657–58
Alpha decay, 325, 329
Alpha particle, 325
Alternating current (AC), 595–98. *See also* Electric current
Alternating current generator, 557, 599–603
  commercial, 611–12
Aluminum-26, 332
Ammeter, 517–18, 565, 646
Ampere, 516
Ampère, André-Marie, 516, 559
Amplitude, 385, 422
Analog meter, 565–66
Animals, 429, 472–74, 551
Antilock braking system (ABS), 180
Antinodes, 422
Appliances
  electrical requirements of, 597
  power ratings of, 252–53, 505
Applied forces, 115
Arc Fault Circuit Interrupters (AFCIs), 598
Aristotle, 82
Armature, 569
Artificial limbs design, 186–87
Atomic mass unit, 334
Atomic number, 319
Atomic theory of matter, 318
Atoms, 318–19
Audible sound waves, 392
Aurora borealis, 551
Average acceleration, 23
Average speed, 14–15
Average velocity, 16–17
  from position-time graph, 28–29

B

Bats, 473
Batteries, 558, 589
Beanbag launcher, 96–97
Bearing design, 186
Beat frequency, 427
Beats, 427–29
Becquerel, Henri, 323
Bells, electric school, 561
Beta decay, 326–27
Beta-negative decay, 326, 329
Beta particle, 326
Beta-positive decay, 326–27, 329
Bimetallic strip, 297, 597–98
Binding energy, 335–36, 342
Biofuel energy, 248
Bohr, Niels, 318
Bohr-Rutherford atomic model, 318–19, 320
Boiling point, 274, 289, 291
Brass, specific heat capacity of, 304–5
Brass instruments, 424, 457
Breaking the sound barrier, 398–99
Brownouts, 255, 505
Buffet (vibration), 470, 471
Building acoustics, 461–63

C

Cadmium shut-off rods, 340
Calandria, 339
Caloric theory, 270, 302
Canadian Deuterium Uranium (CANDU) reactors, 334, 337, 339–40
Canadian Hazardous Products Act, 635
CANDU reactor fuel, 339
Carbon-14, 332, 662
Carbon, near-frictionless, 187
Carbon capture and storage (CCS), 508
Carbon dating, 332
Carbon isotopes, 319–20
Carbon-nitrogen-oxygen cycle, 345
Career pathways, 659
Careers, 5
  accident reconstructionist, 152
  acoustical engineer, 462, 478
  acoustic material designer, 478
  aeronautics engineer, 152, 196, 478
  aerospace industry careers, 470
  aircraft designer or engineer, 469
  archaeologist, 316
  architectural engineer, 88
  astronaut, 165, 196
  astrophysicist, 316, 352
  audio engineer, 458, 478
  audiologist, 452, 478
  audio technician, 396, 406
  auditory neuroscientist, 440
  automotive engineer, 180, 196
  automotive repair technician, 512, 538
  biologist, 316
  biomechanical engineer, 187, 196
  broadcast engineer or technician, 440
  building acoustics designer, 478
  cartographer, 66
  circuit design engineer, 538
  civil engineer, 50, 142, 152, 286–87, 406
  computer service technician, 512, 538
  crane operator, 142, 152
  diagnostic medical ultrasonographer, 440
  digital remastering engineer, 440
  electrical engineer, 614
  electrician, 512, 538, 596, 614
  electromagnetic engineer, 614
  electronics designer, 538
  energy consumption manager, 308
  energy operations manager, 248
  engineer, 8, 50
  forensic audio specialist, 406
  forensic technician or forensic scientist, 139, 152
  gas and oil burner technician, 308
  geomatics technician, 11, 50
  geophysicist, 406
  geothermal heating/cooling engineer, 300, 308
  GIS analysts/applications specialist, 11, 50
  helicopter pilot, 196
  HVAC technician or engineer, 260, 297, 308
  instrument tuner, 440
  laboratory technician, 538
  land surveyor, 88

Careers (*continued*)
  live sound engineer, 406
  materials scientist, 152, 187, 196
  mechanic, 152, 180
  mechanical engineer, 50, 186
  medical biophysicist or physicist, 50, 538
  medical radiation physicist, 352
  military engineer, 50
  motive power technician, 578
  MRI technologist or technician, 352, 572, 578
  musical instrument maker, 478
  music teacher, 478
  music therapist, 478
  naval officer, 60, 88
  network engineer, 538
  nuclear engineer, 260, 340, 352
  nuclear medicine physician or technologist, 352
  nuclear operator, 352
  nuclear physics professor, 260, 352
  occupational therapist, 196
  otolaryngologist, 440
  particle physicist, 551, 578
  personal trainer, 196
  physiotherapist or physiotherapy assistant, 88
  pilot, 88
  power engineer, 506, 538
  power engineering technologist, 578
  power plant manager, 578
  power systems engineer, 248
  power technician, 612, 614
  process engineer, 578
  product design engineer, 418
  prosthesis designer or technician, 152, 187, 196
  quantum computer physicist, 614
  radiation therapist, 321, 352
  radiologist, 406
  recording engineer, 406
  renewable energy consultant, 256
  research scientist (nanoscale electronics), 614
  robotics engineer, 50
  rocket scientist, 152
  science teacher, 85, 406, 614
  sign language interpreter, 478
  sound effects technician, 440
  speaker designer, 406
  speech-language pathologist, 478
  sports footwear designer, 152, 196
  sportswear designer, 184
  structural engineer, 431, 440
  surveyor, 66, 88
  sustainable energy and building technologist, 260
  sustainable energy researcher, 256
  systems engineer, 578
  test pilot, 406
  thermal insulation designer or researcher, 279, 308
  thermodynamics research physicist, 260, 308
  ultrasound technician, 406
  university professor, 50
  vibrations specialist, 406
  vibrations testing engineer, 478
Cars. *See also* Vehicle safety
  brakes, 180
  car body design, 182
  hybrid and electric motors, 570
  race cars, 109, 160
  solenoids in, 561
  tires, 179–80, 189–90
Cats, and hearing, 474
Cellphones, 499
Celsius, Anders, 272
Celsius scale, 272–73
Chadwick, James, 323
Chain reactions, 337
Changes of state, 274, 288–89
Chargers, induction, 591
Chart of nuclides, 320, 335
Chemical energy, 237
Chemical reactions, 323–24
Circuit analysis, 531–35, 536–37
Circuit breakers, 597–98
Circuit diagram symbols, 520, 645
Circuits, electrical, 512–13. *See also* Electric current
  drawing and constructing, 645–46
  household, 596–97
  resistors in, 527–30
Clean coal technology, 508–9
Coal gasification, 508
Coefficient of kinetic friction, 169–70
Coefficient of static friction, 169–70
Coefficients of friction, 169–70, 193–94
Coefficients of sound absorption, 461
Coiled conductors, 559–60, 589
Coldness, 270–71
Commercial AC generators, 611–12
Compass, 548, 549
Compass rose, 60–61
Complex wave motion, 382–83
Component vector, 68, 656–57
Compressions, 382, 451
Computer hard drive, 546
Concert hall, 448
Condensation point, 274, 289, 291
Conduction, thermal, 276, 279
Conductors
  moving with electricity, 563–64
  superconductors, 525
  thermal, 279
Conservation of energy, 257–58
Conservation of energy, law of, 237–41, 303, 592–93, 606
Conserving energy, 249, 360–61
Constructive interference, 416–17, 436–37
Contact forces, 116
Controlled experiments, 640–41
Controlled nuclear fusion, 345–46
Convection, 277, 278
Convection current, 277
Conventional cooling systems, 297
Conventional current (electric), 514–15, 553, 554
Conventional heating systems, 296, 297
Cooking with induction cooker, 590
Cooling graph, 290
Cooling systems, 296–99
Correlational studies, 641–42
Coulomb, 511
Crash testing, 181
Crest, of wave, 385, 437
Critical mass, 337
Current. *See* Electric current
Current law, Kirchhoff's, 519–20, 521
Cyclical motion, 378
Cyclotron, 323

D

Dalton, John, 302, 318
Dampers, 465
Damping, 430, 431
Daughter atom, 325
Deafness, 452
Decibels, 395
Defense Advanced Research Projects Agency (DARPA), 187
Delta, 9
Democritus, 318
Destructive interference, 416–17
Deuterium, 320
Digital multimeter, 646
Direct current (DC), 516–17. *See also* Electric current
Direct current generators, 603
Direct current motor, 567–71, 576–77
Directed line segment, 11
Direction, 8–9
  of induced current, 592–93
  right-hand rules for current and magnetic fields, 554, 560, 564
  in two dimensions, 60–61
  of vectors, 655
Displacement, 9
  adding in two dimensions, 66–71
  determining from velocity-time graph, 25–26
  equation for uniformly accelerated motion, 36–37
  for motion in straight line, 10–11
  time calculation, 18

  for two motions in opposite directions, 12
  in work equation, 222–26
Displacement vectors
  adding by components, 69–71
  in two dimensions using scale diagrams, 61–64
Distance, 8
  and loudness, 396
Diving, 238–39
Dolphins, 472–73
Doppler effect, 433–35
Dot products, 224
Dozois-Prevost, Marilou, 222, 223, 226
Drag (fluid friction), 169, 398
Drop-tower rides, 594
Drums, 458–59
Dynamics, 114

E

Ears, human, 450–52
Earth
  magnetic poles of, 548
  tectonic plates and seismic waves, 466–68
Earthquakes, 466–67
Echo, 392
Echolocation, 472–73
Edison, Thomas, 595
Efficiency, 242–43
  of energy and power plants, 506–7
  of thermal energy transformations, 280
  of transformers, 609
  of transmission wires, 610
  of wave motion, 416
Egg crash test, 204–5
Einstein, Albert, 83, 148–49, 334
Elastic energy, 237
Elastic medium, 379
Electrical circuits. *See* Circuits, electrical
Electrical energy, 236, 505–6
Electrical energy transfer, 510
Electrical heating systems, 296
Electrical power, 252–54, 504–5
Electrical power grid, 255, 557, 595, 611. *See also* Power plants
Electrical requirements of appliances, 597
Electrical resistance, 523–26
Electrical safety, 638
Electric current, 516–18
  alternating current (AC), 595–98
  conventional current and electron flow, 514–15, 553–54
  direct current (DC), 516–17
  and electromagnetic induction, 588, 592–93
  Kirchhoff's current law, 519–20, 521
  representation with magnetic fields, 554–55
  in transformers, 608
  and transmission efficiency, 610
Electric generators, 599
  alternating current generator, 557, 599–603, 611–12
  direct current generator, 603
Electricity, 498, 502, 504
  conventional current and electron flow, 514–15
  relationship to magnetism, 546, 553
  wireless, 557–58
Electricity generation, 599–604
Electric motor, 563
  direct current motor, 567–71, 576–77
Electric potential, 511, 519
Electric potential difference, 511–13
Electromagnet, 560, 575
Electromagnetic force, 121, 553
Electromagnetic induction, 586, 588–91, 599, 613
Electromagnetic radiation, 236
Electromagnetism, 546
Electron capture, 327, 329
Electron flow model of current, 515, 554
Electronic speed limiters, 44–45
Electronic stability control (ESC), 181
Electrons, 318, 334
Electron-volt, 335
Electrostatic force, 324
Elephants, 473
Empire State Building, 465
Endothermic chemical reaction, 324
EnerGuide label, 254
Energy, 216, 230–35
  mass-energy equivalence, 334
  output of fusion and fission reactions, 343–44
  produced in Canada, 217
  sources of, 245–48
  types of, 236–37
Energy efficiency and power plants, 506–7
Energy ratings and cost of electricity, 252–54
Energy resources, 245–48
Energy transformations, 237
  efficiency improvement, 244–45
  quantifying, 238–40
Environmental concerns
  of battery disposal, 558
  energy use and production, 217
  global warming, 288, 298
  radioactive waste disposal, 340
Equations, mathematical, 652–54
Equivalent resistance, 527–30
Evaporation, 289
Excited state of atom, 318
Exothermic chemical reaction, 324
External forces, 116

F

Fahrenheit, Daniel Gabriel, 272
Fahrenheit scale, 272
Faraday, Michael, 563, 588, 589
Faraday's ring, 588, 589, 605
Father Michael McGivney Secondary School, 360
Fields, 548
  force, 164, 548
  magnetic, 548–55, 574, 575–76, 589–90
Field studies, 643
Fire safety, 638
First aid, 638
First harmonic, 423, 454, 455, 458
Fission, nuclear. *See* Nuclear fission
Fissionable isotopes, 336
Fixed-end reflections, 421
Fluid friction, 169
Flutter, 470–71
Footwear design, 185
Forced-air heating systems, 296
Force diagrams, 114–15, 117–18
Force field, 164, 548
Force of gravity, 116, 121, 162–67
Force-position graph, 227
Forces, 108. *See also Specific types*
  automotive technology applications, 179–83
  designing technology by using, 160
  effect on motion of objects, 112–13
  fundamental, 121
  measurement of, 114
  research applications, 186–87
  sports applications, 184–85
  types of, 114–22
  work done by, 222–27
Force sensor, 114
Fossil fuels, 245
Franklin, Benjamin, 514–15
Free-body diagrams (FBD), 115
  determining net force, 119–20
  and first law of motion, 124–26
Free-end reflections, 420–21
Free fall, 40
  and air resistance, 162–63
  and terminal velocity, 43
Freezing point, 274, 289, 291
Frequency
  fundamental, 423, 454, 455, 458
  human hearing, loudness, and, 475
  and pitch in musical sound, 454–56
  of wave, 386
Friction, 115, 168–71
  coefficients of, 169–70, 193–94
  factors affecting, investigation, 192–93
Fuel bundles, 339
Fundamental forces, 121
Fundamental frequency, 423, 454, 455, 458

Furnaces, 280
Fuses, 597
Fusion, nuclear. *See* Nuclear fusion
Fusion (melting change of state), 289

G

Galileo Galilei, 82–83, 123–24
Galvanometer, 565–66
Gamma decay, 328, 329
Gases
  and changes of state, 274, 288–89
  vibrations and particle behaviour in, 379–80
Generators and power generation. *See also* Electric generators
  nuclear power generation, 334–41
  off-the-grid energy generation, 255–56
  steam generator, 339
Geometric wave characteristics, 385–86
Geometry equations, 652
Geophysical exploration, seismic, 467–68
Geothermal energy, 248, 268
Geothermal systems, for heating and cooling, 298–99, 300–301
Giambattista, Benedetti, 82
Glaciers, 288
Global positioning system (GPS) technology, 58
Global warming, 288, 298
Golf club design, 184–85
Graphs. *See also* Acceleration-time graphs; Position-time graphs; Velocity-time graphs
  force-position, 227
  heating and cooling of water, 290, 305–6
Gravitational field strength, 164
Gravitational force, 116, 121, 162–67
Gravitational potential energy, 233–34, 236
Gravity
  acceleration due to, 40, 191–92
  effect on motion of objects, 7
  and second law of motion, 134–35
Gray, Stephen, 514
Greek alphabet, 661
Ground Fault Circuit Interrupters (GFCIs), 598
Ground state of atom, 318
Ground wire, 597
Guitars, 456

H

Half-life, 330–33
Harmonics, 423, 454, 455, 458
Hawking, Stephen, 149
Hawking radiation, 149
Hazardous products and safety, 635, 636
Headrests in vehicles, 125
Hearing, in humans, 450–53, 475
Hearing aids, 452
Heat
  compared to thermal energy, 276–80
  quantity of, 281–83
Heat capacity, 281–87
Heating graph, 290
  of water, 305–6
Heating systems, 296–99
Heat pumps, 298–99, 300–301
Heat safety, 637–38
Heavy water, 337
Heinkel, Ernst, 398
Hertz, 386
Higgs boson, 551
Hoover, Bob, 399
Hot water heating systems, 296
House cats, 474
Household circuits, 596–97
Household Hazardous Product Symbols (HHPS), 635
Human ears, 450–52
Human hearing, 450–53, 475
Human perceptions of sound intensity, 395
Human power, 258–59
Hydroelectricity, 247–48
Hydrogen atom, 319, 320
Hydroplaning, 179–80

I

Ice, 289
Ice skating, 185
Induced current, 588
  direction of, 592–93
Induction chargers, 591
Induction cooking, 590
Inertia, 123–24
Infrasonic waves, 392, 473
In phase, 386
Insect infestation, 348–49
Instantaneous velocity, 27–29
Instruments, musical, 424, 455–59, 476, 486–87
Interference of waves, 416–19, 422, 436–37
Internal combustion engine, 280
Internal forces, 116
International Space Station (ISS), 165
Ionizing radiation, 329
Isolated system, 334
Isotopes, 319–20
  fissionable, 336
  radio-, 320, 321, 662–63
  stable and unstable, 324
ITER project, 346

J

Jet engines, 398–99
Joule, 222, 234, 271, 281, 303
Joule, James Prescott, 222, 302–3
Joule's law, 302
Joules per coulomb, 511
Joules per kilogram, 291
Junger, Waldmar, 558

K

Kelvin, Lord, 272
Kelvins, 272
Kelvin scale, 272–73
Kilograms, 165
Kilowatt hours, 252–53, 505
Kinematics, 2, 8
  and Newton's laws of motion, 145–46
Kinetic energy, 230–33, 236
Kinetic friction, 168–69, 175–77
Kinetic molecular theory, 270–71
Kirchhoff, Gustav, 519
Kirchhoff's current law, 519–20, 521
Kirchhoff's laws, 519–22
Kirchhoff's voltage law, 519, 521

L

Laboratory reports, 643–44
Laboratory safety, 635, 637–38
Laboratory skills and techniques, 645–46
Large Hadron Collider (LHC), 551
Latent heat, 291–93
Latent heat of fusion, 291–93
Latent heat of vaporization, 291–93
Law of conservation of energy, 237–41, 303, 592–93, 606
Law of conservation of mass-energy, 334
Law of electromagnetic induction, 588
LEED (Leadership in Energy and Environmental Design), 279
Lenz, Heinrich, 592
Lenz's law, 592–94
Light bulbs, 242, 244
Linear density, 390
Linear equations, 654
Linear induction motor, 586
Linear motion, graph comparisons, 31–35
Liquids
  and changes of state, 274, 288–89
  vibrations and particle behaviour in, 379
Liquid water, 289
Load limiters, 182
Lobsters, 551
Logarithms, 395
Longitudinal waves, 381–82, 383
  P-waves, 466
Loudness, 396, 427, 454, 475

M

Mach, Ernst, 394
Mach number, 394
Maglev trains, 548, 550
Magnetically coupled resonators, 558
Magnetic confinement fusion, 345–46
Magnetic field lines, 549–50

Magnetic fields, 548–55, 574, 575–76, 589–90
Magnetic resonance imaging (MRI), 551, 572–73
Magnetism, relationship to electricity, 498, 546, 553
Magnetite, 548
Magnets, 551
Mass compared to weight, 165
Mass damper, 465
Mass defect, 335–36, 343–44
Mass-energy equivalence, 334–36
Mass number, 319, 320, 342
Material Safety Data Sheet (MSDS), 635
Math skills, 650–58
Measurement uncertainty, 650–52
Mechanical energy, 235, 236
Mechanical resonance, 464
Mechanical waves, 378, 381–84
Mechanical work, 222, 232–33
Media boundaries, 420, 422
Medical diagnostic imaging technologies, 572–73
Medical treatments, 321
Medium, 378
Mega-electron volt, 335
Megawatt hours, 505
Melting point, 274, 289, 291
Metal detectors, 590
Microgravity, 165
Moon, seismic exploration of, 468
Motion, 8
  down a ramp, investigation, 48–49
  effect of forces on object, 112–13
  explained using third law of motion, 138
  and friction, 174–77, 194–95
  of object falling straight down, 40–41
  of object thrown straight up, 41–42
  projectile, 76–81, 86–87
  translational molecular, 379
  types of, in position-time graphs, 19
Motion in straight line, 6
Motion in two dimensions, 58–88
  algebraic approach, 66–74, 657–58
  determination of, 58
  projectile motion, 76–81, 86–87
  scale diagram approach, 60–65, 656–57
Motion sensor, 47
Motion with non-uniform velocity, 18
Motion with uniform acceleration, 27
  five key equations for, 36–39
Motion with uniform or constant velocity, 18
Motor principle, 563–66
Motors
  direct current, 567–71, 576–77
  for hybrid and electric cars, 570
  linear induction, 586
Moving objects
  conductors with electricity, 563–64
  continuously with direct current motor, 567–71
  effects on society and environment, 6
  kinetic energy of, 230–33
Music, 454
Musical instruments, 424, 455–59, 476, 486–87
Musical notes, 427
Musical sound, 454
  standing waves and, 423–24

N

Near-frictionless carbon, 187
Negative work, 226–27
Net forces
  calculating, 119–20
  second law of motion applied, 132–33
Net motion, 378
Neutron moderation, 337
Neutrons, 318, 334
Newton, 114
Newton, Isaac, 114, 124, 148–49
Newton, SI unit, 114
Newton metre, 222, 234
Newton's first law of motion, 123–28
  applications of, 128
  and free-body diagrams, 124–26
  testing it, investigation, 127
Newton's laws
  and kinematics, 145–46
  and tension, 142–44
Newtons per kilogram, 164
Newton's second law of motion, 130–35
  and gravity, 134–35
  investigation, 150–51
  mathematical representation of, 131–33
  variables involved in, 130–31
Newton's third law of motion, 137–41
  in calculations, 139–40
Nodes, 422
Noise, 414, 454
Noise-cancelling headphones, 414, 418
Noise pollution, 400–401
Non-renewable energy resources, 245–46
Normal force, 115
Northern lights, 551
Nuclear decay, 317. *See also* Radioactive decay
Nuclear energy, 237
  applications of, 316
  benefit or hazard, investigation, 350–51
  as source of energy, 245–46
Nuclear fission, 245–46, 323, 336–38
Nuclear fuel, 336–38
Nuclear fusion, 245, 342–47
  controlled, 345–46
Nuclear power generation, 334–41
Nuclear reactions, 324–28
Nuclear reactors
  CANDU, 334, 337, 339–40
  power plants, 246
  Tokamak magnetic confinement fusion, 346
Nuclear stability, 342–44
Nucleons, 318
Nuclide chart, 320, 335
Numerical prefixes, 661

O

Oberth, Hermann, 399
Observational studies, 642–43
Oersted, Hans Christian, 553
Oersted's principle, 553–55
Off-the-grid energy generation, 255–56
Ohm, 524
Ohm, Georg Simon, 524
Ohmmeter, 525
Ohm's law, 524–25
Oscillation, 387
Out of phase, 386
Overtones, 423

P

Parallel circuits, 512, 519–22
  connecting resistors, 528–30
Parent atom, 325
Particle accelerators, 551
Particle behaviour in different media, 378–80
Passive solar design, 246–47
Payette, Julie, 165
Pendulums, 464, 465
Percussion instruments, 458–59
Period, of wave, 386
Periodic table of elements, 319, 664–65
Pest control, 348–49
Phase, of wave, 385
Phase shift, 385–86
Photon, 328
Photovoltaic cells, 246, 247
Physical constants, 662
Physical states of matter, 274, 288–93
Pianos, 455
Pinna (external ears), 450, 473, 474
Pistorius, Oscar, 187
Pitch, 454
Plasma, 345
Plato, 82
Pogo effect in rockets, 471
Position, 9
Position-time graphs, 16
  determining types of motion from, 19
  of objects moving with accelerated motion, 21–22
  relationships among linear motion graphs, 32

Positive work, 226–27
Positron, 326
Potential energy, 233, 236–37
Power, 250–54
Power equation, 504
Power grid, electrical, 255, 557, 595, 611
Power plants. *See also* Nuclear reactors
  building a model, 622–23
  efficiency of, 506–7
  and electrical grid, 610–12
Power ratings of appliances, 252–53, 505
  electrical requirements of, 597
Prefixes, numerical, 661
Pressure, in sound waves, 395
Pressure waves, 385. *See also* Longitudinal waves
Pretensioner, 181
Primary waves (P-waves), 466
Principia Mathematica (Newton), 124, 148
Principle of superposition, 416, 418, 422
Principle of thermal energy exchange, 283–85
Products, of chemical reactions, 323
Projectile motion, 76–81, 86–87
Projectiles, 76
Prosthesis design, 186–87
Proton-proton chain, 345
Protons, 318, 334
Pulse test, 470
Pythagorean theorem, 652

Q
Quadratic formula, 652–53
Quality of sound, 454, 455, 458
Quantity of heat, 281–83
Queen Mary, 436

R
Race cars, 109, 160
Radiant energy, 236
Radiation, 278, 320
Radioactive decay, 323–29, 324
  measuring rate with half-life, 330–32
Radioactive tracers, 321
Radioactivity, 323
Radioisotopes, 320, 321, 662–63
Radionuclide therapy (RNT), 321
Range, of projectile, 76
Rarefactions, 382, 451
Rates of change, 16
Reactants, in chemical reactions, 323
Reaction forces, 137–41
  force of static friction, 174
Reactors
  CANDU, 334, 337, 339–40
  Tokamak magnetic confinement fusion, 346
Reference level, 233
Refrigerants, 297, 298, 299
Renewable energy resources, 245, 246–48
Research skills, 648–49
Resistance, electrical, 523–26
Resistance, equivalent, 527–30
Resistors, 523, 527–30
Resonance, 430, 431
Resonant frequency, 430, 431, 457–58
Resonator, 455
Resultant force, 119. *See also* Net forces
Resultant vector, 61
Reverberation time, 461–62
Right-hand rule
  for the motor principle, 564
  for a solenoid, 560
  for a straight conductor, 554
Rise, 16
Risk-benefit analysis model, 649
River crossing problems, 72–74
Rocket engines, 399
Rockets, pogo effect, 471
Rogue waves, 436–37
Roller coasters, 586
Rolling friction, 169
Rounding in calculations, 15
R-2000 program, 279
Rumford, Count, 270
Run, 16
Running shoes, 185
Rutherford, Ernest, 318, 323

S
Safety
  of aircraft, 469–71
  of CANDU fission reactors, 340
  conventions and symbols, 635
  electrical systems, 597–98
  forces in automotive technology, 179–83
  in laboratory, 635, 637–38
  marine, and rogue waves, 436–37
  of sound intensity, 396, 400, 452
  structures and waves, 448, 464–65
Scalar quantity, 9
Scale diagram approach to motion in two dimensions, 60–65, 656–57
School buildings, 360–61
Science, technology, society, and environment (STSE), 3, 648
Scientific inquiry, 639–44
Scientific notation, 650
Scientific publications, 647
Scott, David, 82
Seat belts in vehicles, 128, 181–82
Secondary waves (S-waves), 466
Seismic geophysical exploration, 467–68
Seismic waves, 466–68
Series circuits, 512, 519–22
  connecting resistors, 527
SI base units, 8, 660
SI derived units, 8, 23, 660
Significant digits, 650–51
Simple harmonic motion, 387
Skydiving, 162, 163
Skyscrapers, 465
Sliding friction, 169
Slope of a line, 16
Snowboarding, 220–21
Solar energy, 246–47
Solenoids, 559–61, 589
Solids
  and changes of state, 274, 288–89
  vibrations and particle behaviour in, 379
Soljacic, Marin, 558
Sonic booms, 399
Sound, 372
  acoustics, 461–63
  as longitudinal waves, 382
  musical, 423–24, 454
Sound absorption coefficients, 461
Sound barrier, 398–99
Sound energy, 236
Sound intensity, 395–96
Sound safety, 396, 400, 452
Sound waves
  music and building safety applications, 448
  in nature with animals, 472–74
  properties of, 392–97
Speakers, subwoofers, 561
Specific heat capacity, 281
  of brass, 304–5
Specific latent heat, 291–93
Specific latent heat of fusion, 291–93
  for ice, 306–7
Specific latent heat of vaporization, 291–93
Speed
  average, 14–15
  of sound, 393–95, 404–5
  terminal, 163
  wave, 386–87, 388–91, 438
Speed limiters, electronic, 44–45
Split ring commutator, 567, 570, 603
Sports in motion, 3
Spring scale, 114
Square second, 23
Stable isotopes, 324
Standing waves, 422–26, 431, 439
States of matter, 274, 288–93
  plasma, 345
Static friction, 168
  and motion, 174–75
  solving problems, 173–75
Steam generator, 339
Stellar fusion, 345
Step-down transformers, 605
Step-up transformers, 605, 606
Sterile insect technique (SIT), 348
Stimulus (in vibration), 381
Stringed instruments, 455–57

String tension, 390–91
Strong nuclear force, 121, 324
Structural safety, 431, 448, 464–65
Structure (building) acoustics, 461–63
Sublimation, 289
Superconducting electromagnets, 345, 346
Superconductors, 525
Superposition, principle of, 416, 418, 422
Sustainable energy plan, 360–61
Sweep test, 470
Sympathetic vibrations, 464, 465
System diagrams, 114

T

Tacoma Narrows Bridge, 464
Targeted muscle reinnervation (TMR), 187
Technetium-99m, 316, 321, 662
Tectonic places, 466–67
Teflon, 187
Temperature, 271–72
  and thermal energy, 275
  thermal energy and physical state, 274
  and wave speed, 389
Temperature scales, 272–73
Tension, affecting wave speed, 390
Tension (force), 115
  and Newton's laws of motion, 142–44
Terminal speed, 163
Terminal velocity, 43
Tesla, Nikola, 557, 595
Tesla coil, 557
Thermal conduction, 276, 279
Thermal conductors, 279
Thermal contraction, 287
Thermal energy, 236, 268
  compared to heat, 276–80
  defined, 271
  and temperature, 275
  temperature and physical state, 274
  transfer methods, 276–80
Thermal energy exchange, principle of, 283–85
Thermal energy transformations, 280
Thermal expansion, 286
Thermal insulators, 279–80
Thermal neutrons, 337
Thermometers, 271–72
Thermos bottle, 280
Thermostats, 297
Thirsk, Robert, 165
Thompson, Benjamin, 270
Thomson, J. J., 515
Thomson, William, 272
Tidal energy, 248
Time-based wave characteristics, 386–87
Time of flight, 76
Tokamak magnetic confinement fusion reactor, 346
Traction control, 180–81
Trains, Maglev, 548, 550
Transformer efficiency, 609
Transformers, 605–9
Translational molecular motion, 379
Transmission efficiency, 610
Transmission lines/wires, 510, 610
Transmission of waves, 422
Transmutation of nuclear reaction, 325
Transverse waves, 381, 383
  S-waves, 466
Trigonometry, 653–54
Tritium, 320
Trough, of wave, 385, 437
Tsunamis, 373, 466–67

U

Ultrasonic waves, 392
Ultrasound, 392
Uncertainty in measurements, 650–52
Uniformly accelerated motion. *See* Motion with uniform acceleration
Uniform vertical acceleration, 40
Unit analysis, 654–55
Units, SI base, 8, 660
Units, SI derived, 8, 23, 660
Units, use of, 652
Units of measure, 8, 395
  ampere, 516
  coulomb, 511
  electron-volt, 335
  hertz, 386
  joule, 222, 234, 271, 281, 303
  joules per coulomb, 511
  joules per kilogram, 291
  kelvins, 272
  kilograms, 165
  kilowatt hours, 252–53, 505
  mega-electron volt, 335
  megawatt hours, 505
  newton, 114
  newton metre, 222, 234
  newtons per kilogram, 164
  ohm, 524
  volt, 511
  voltage, 511
  watt, 250, 504
  watts per square metre, 395
Universal wave equation, 388–89
Unstable isotopes, 324
Uranium-235, 336–38, 339, 663

V

Vaporization, 289
Vectors, 9, 655–58
  addition, 10, 656–58
  breaking down into two perpendicular components, 68–69, 656–57
  resultant, 61
  subtraction, 10
Vector scale diagrams, 11–12, 61–64, 656–57
Vehicles. *See* Cars
Vehicle safety, 179–83
  airbags, 182
  car body design, 182
  car brakes, 180
  car tires, 179–80, 189–90
  crash testing, 181
  electronic speed limiters, 44–45
  headrests, 125
  seat belts, 128, 181–82
  stability control, 180–81
Velocity
  adding in two dimensions, 71–74
  average, 16–17, 28–29
  detemining final, of falling object, 41
  instantaneous, 27–29
  terminal, 43
  uniform, investigation, 47–48
Velocity-time graphs, 21
  determining acceleration from, 22–24
  determining displacement, 25–26
  relationships among linear motion graphs, 32–34
Vibrations, 376, 378–80. *See also* Waves
  and structural safety, 464–65
  wave motions, investigation, 402–3
Violins, 456
Volt, 511
Volta, Alessandro, 511
Voltage, 511, 596
  in transformers, 607
Voltage law, Kirchhoff's, 519, 521
Voltmeter, 512, 565–66, 646
von Braun, Wernher, 399
von Ohain, Hans, 398

W

Warmth, 270–71
Waste disposal, radioactive, 340
Water
  changes of state, 289
  heating and cooling graphs, 290, 305–6
  a special liquid, 293–94
Water vapour, liquid, and ice, 289
Watt, 250, 504
Watt, James, 250
Wave characteristics, 385–87
Waveform, 385, 476
Wave interactions, 414
Wave interference, 416–19, 422, 436–37
Wavelength, 385, 389
Waves, 372, 376. *See also* Sound waves
  complex wave motion, 382–83
  interference of, 416–19, 422, 436–37
  mechanical, 378, 381–84
  at media boundaries, 420–26

Waves (*continued*)
  seismic, 466–68
  standing, 422–26, 431, 439
  two-dimensional, investigation, 403–4
Wave speed, 386–87, 388–91, 438
Weak nuclear force, 121
Weight compared to mass, 165
Weightlessness, 165
Weightlifting, 222
White, Shaun, 220
Whittle, Sir Frank, 398
Wind energy, 248
Wind instruments, 457–58
Winds and structural safety, 464–65
Wind turbines, 217, 604
Wireless electricity, 557–58
Work, 222–28
  done by changing force, 227
  done by constant force, 222–26
  graphical representation of, 227
  positive and negative, 226–27
Work-energy principle, 232
Workplace Hazardous Materials Information System (WHMIS), 635, 636

Y

Yeager, Chuck, 399

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